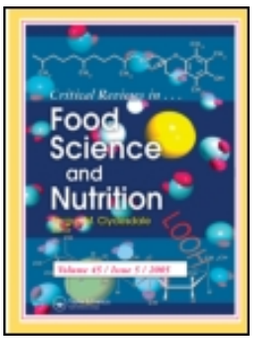

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Technologies and Mechanisms for Safety Control of Ready-to-eat Muscle Foods: An Updated Review

JIANG JIANG[1] and YOULING L. XIONG[2]

[1]College of Food Science and Synergetic Innovation Center of Food Safety and Nutrition, Jiangnan University, Wuxi, Jiangsu, China
[2]Department of Animal and Food Sciences, University of Kentucky, Lexington, Kentucky USA

Ready-to-eat (RTE) muscle foods refer to a general category of meat and poultry products that are fully cooked and consumable without reheating. These products, including whole and sliced pork, beef, turkey, chicken, and variety of meats, in the forms of ham, roast, rolls, sausage, and frankfurter, are widely available in the delicatessen section of retail stores or various food service outlets. However, difficulties in avoidance of contamination by foodborne pathogens, notably Listeria monocytogenes, *during product postlethality repackaging render RTE meats labile to outbreaks. Accordingly, the USDA-FSIS has established processing guidelines and regulations, which are constantly updated, to minimize foodborne pathogens in RTE products. Technologies that complement good manufacturing practice have been developed to control RTE meat safety. Among them, various antimicrobial product formulations, postpackaging pasteurization (thermal and nonthermal), and antimicrobial packaging are being used. Through these efforts, outbreaks linked to RTE meat consumption have substantially reduced in recent years. However, the pervasive and virulent nature of L. monocytogenes and the possible presence of other cold-tolerant pathogens entail continuing developments of new intervention technologies. This review updates existing and emerging physical and chemical methods and their mode of action to inactivate or inhibit threatening microorganisms in RTE muscle foods.*

Keywords Ready-to-eat, cooked meat, *Listeria monocytogenes*, antimicrobials, postpackaging pasteurization, packaging

INTRODUCTION

A ready-to-eat (RTE) meat product is defined as a meat or poultry product that is in a form that is edible without additional preparation to achieve food safety (9 Code of Federal Regulations, Part 430). These types of products are enormously popular due to the convenience, product variety, and acceptable palatability it provides. Although an RTE product is usually consumed as is, it may receive additional preparation such as warming to make the product more palatable. In general, RTE products are manufactured at intermediate temperatures with the final product temperatures typically in the 65–75°C range. They differ from high temperature-processed products that receive sterility or total microbial lethality, for example, canned meats. Hence, except for certain fermented, dry or semi-dry, and high-acid products, RTE muscle foods generally require refrigeration, hence, are also referred to as cold cuts.

RTE meat and poultry products can be grouped into two main categories: deli meats and hotdogs. Deli meats are sold at the delicatessen counter, which include but are not limited to: baked or boiled ham, turkey ham, chicken roll, roast beef, corned beef, bologna, and salamis. These products may be presliced, or intact as a log or loaf that are sliced at the deli upon the request of the customer. They are normally assembled in a sandwich, mixed into a salad, or simply cut into small pieces for consumption without further cooking. RTE hotdogs include a variety of frankfurters and wieners made from chicken, turkey, pork, and beef.

RTE meat products have a long history, emerging at the advent of the refrigeration system. RTE products became increasingly popular in western countries in recent years due to the perceived healthiness (lean), generally good taste, and most importantly, the convenience they offer. According to a recent survey, on a given day, 20 to 50% of the Australian population consumes RTE meats (NSW Food Authority, 2009).

Address correspondence to Youling L. Xiong, Department of Animal and Food Sciences, University of Kentucky, Lexington, KY 40546, USA. E-mail: ylxiong@uky.edu

There is not a similar survey done in the United States, but the daily consumption of RTE luncheon meats is a commonplace among the workforce and even in a typical household.

Despite the popularity, RTE meat and poultry are labile to foodborne outbreak associated with *Listeria monocytogenes*, a pathogen that can grow at refrigeration temperatures and tolerate salt and nitrite (McClure et al., 1997; Ivy et al., 2012). Due to the high mortality rate (20 to 30%) associated with listeriosis, there is a zero tolerance of *L. monocytogenes* in RTE meat products in the United States. Since 1983, the United States Department of Agriculture (USDA)—Food Safety and Inspection Service (FSIS) has been conducting regular microbiological testing on RTE meats to ensure product safety. In 2003, the Food and Drug Administration (FDA)/USDA risk assessment for *L. monocytogenes* identified deli meats as the highest-risk food from the 23 types of RTE foods examined (FDA, 2003). This risk assessment is strongly supported and justified by tests in subsequent years that confirmed *L. monocytogenes* to be the far prevalent pathogen detected on postpackaging contaminated RTE meats (FSIS, 2012).

The risk of RTE meat and poultry products to *L. monocytogenes* outbreaks proves to be a global concern. As in the United States, *L. monocytogenes* has been identified as the dominant pathogen in contaminated RTE meats that elicit illnesses in European countries. Reported incidences include countries like United Kingdom (Gormley et al., 2010a; 2010b), Spain (Cabedo et al., 2008), and Nordic countries (Gudbjörnsdóttir et al., 2004) where the *L. monocytogenes* contamination rates range from 0.37 up to 12.5%. In 2008, a widespread listeriosis outbreak in Canada that involved 22 deaths and 57 confirmed cases was linked to contaminated RTE deli meats (cold cuts) from a leading meat processing plant in Toronto. The high risk rate of RTE products is due to the absence of subsequent cooking when contaminated products from slicing and repackaging are directly consumed (which is a common practice). In addition, the ability of *L. monocytogenes* to proliferate at refrigerated temperatures, the long shelf-life (storage time) of RTE meats, and the rich nutrients RTE products provide for the organism increase the risk (Seman et al., 2002; Sofos and Geomaras, 2010). Therefore, even though the initial counts of *L. monocytogenes* in a contaminated RTE product are usually low, the population can reach a high level during storage to cause listeriosis.

To minimize the risk of *L. monocytogenes* contamination, in 2003, the FSIS established a rule on controlling *L. monocytogenes* on RTE meat and poultry products requiring processors to take one or more specific steps to ensure the absence of this ubiquitous and pervasive disease agent (FSIS, 2003). In particular, the rule requires RTE meat processors to adopt one of three designated "Alternatives" to control *L. monocytogenes* on their products. In Alternative 1, the processor uses both a postlethality treatment that reduces or eliminates *L. monocytogenes* and an antimicrobial agent in the product formulation or process that suppresses or limits *L. monocytogenes* growth throughout product shelf-life. In Alternative 2, the processor uses either a postlethality treatment that reduces or eliminates *L. monocytogenes* or an antimicrobial agent or process that suppresses or limits *L. monocytogenes* growth throughout product shelf-life. In Alternative 3, only sanitation measures are relied upon to control *L. monocytogenes*. Alternatives 1 and 2 involve the use of either or both processing and antimicrobial additives, and the antimicrobial ingredients at the permissible application levels must be validated for their effectiveness in inhibiting the growth of *L. monocytogenes* by 1 to 2 log through the duration of the product shelf-life. For Alternative 3, because no antimicrobial treatments are applied, additional regulations and scrutiny apply and the processor must establish strict sanitation and robust good manufacturing practices.

The safety control of RTE meat and poultry products involves further regulatory actions. In 2011, the FSIS published detailed processing guidelines to assist meat and poultry processors achieving adequate lethality of cooked RTE products prior to storage (FSIS, 2011). The guidelines list various, product-specific temperature-cooking time combinations to eliminate *L. monocytogenes* and other pathogens, including *Salmonella*, *Escherichia coli* O157:H7, *Campylobacter* spp., *Clostridium botulinum*, and *C. perfringens*. To assist processors, the FSIS also has developed and made easily accessible model programs to minimize pathogen threats.

Tremendous efforts have been made in the food industry on developing hurdle technologies to minimize postlethality contamination and growth of pathogens, concentrating on *L. monocytogenes*. Postpackage thermal pasteurization (steam or hot water) and the incorporation of antimicrobial additives in the product formulation are the most common approaches to controlling *L. monocytogenes* in RTE products. Recently, nonthermal pasteurization processes, such as irradiation and high-pressure treatments, have been proposed. Sodium lactate and sodium diacetate are two additives widely used to suppress the growth of *L. monocytogenes*, but a number of other emerging antimicrobials are being developed or are awaiting the regulatory approval. Furthermore, antimicrobial packaging technologies have shown promise as an intervention method to prevent pathogen growth on RTE meats.

This review is an update of the technologies currently available to control *L. monocytogenes* and other foodborne pathogens in RTE meat and poultry products, which include new and emerging technologies. The mechanisms underlying the bacteriocidal or bacteriostatic effects by the specific physical and chemical methods are discussed. For related coverage of the subject, readers are referred to several other reviews, for example, Zhu et al. (2005) and Knipe (2010).

POSTPACKAGE PASTEURIZATION

In-package pasteurization, that is, postlethality or postcooking treatments of repackaged products, is applied to destroy microorganisms on the cooked product surface. This is achieved through either thermal or nonthermal processes.

Thermal processes for postlethality pasteurization include brief heating of repackaged RTE products in hot water or steam for specific durations. Nonthermal processes include irradiation treatments and high-pressure processing. In-package pasteurization is often done in combination with other interventions, for example, antimicrobial additives and antimicrobial packages to create a hurdle that are able to effectively inhibit the growth of *L. monocytogenes* and other potential microbial threats (Bangel, 2012).

Thermal Treatments

Postpackage pasteurization of RTE meats is commonly done by submersion heating. Muriana et al. (2002), using heating at 90.6–96.1°C for two minutes, showed 2 to 4-log reductions of a cocktail of four strains of *L. monocytogenes* artificially inoculated on the surface of packaged RTE deli hams. For low-fat turkey bologna, heating in an 85°C water bath for 10 seconds inactivated all *L. monocytogenes* (6-log reductions) cells inoculated on the product surface (McCormick et al., 2003). Murphy et al. (2005) compared ambient steam (100°C) in-package pasteurization with pressurized steam (131°C) pasteurization to reduce *L. monocytogenes* from fully cooked RTE bologna. A 2-log reduction of *L. monocytogenes* was achieved in two seconds by pressurized steam pasteurization and 2.5 minutes by ambient steam pasteurization. Because of the extremely short treatment time, the flash pressurized steam pasteurization has the advantage of not affecting the quality of RTE products.

It is important to note that the roughness of the product surface can influence the effectiveness of thermal treatments because imperfections and the presence of crevices and pockets can harbor and shield microorganisms (Houben and Eckenhausen, 2006). Furthermore, purge of cold juice from the interior of RTE products during postlethality thermal pasteurization could increase the survival of *L. monocytogenes*. Both hot water and steam pasteurization processes are more effective when RTE products also contain antimicrobial additives, for example, sodium lactate and sodium diacetate, and the treated products tend to have a longer shelf-life.

Nonthermal Treatments

Nonthermal processing has been applied to reduce or eliminate postlethality pathogen contamination on RTE meat and poultry products. Nonthermal pasteurization processing has the advantage of minimally affecting the quality RTE products when compared with thermal pasteurization. Ionizing radiation, including radiations with γ-ray, x-ray, and electron beam (E-beam or β-ray), and high pressure treatment show promise to eliminate pathogens and their growth on postlethality RTE meats.

Irradiation

In principle, irradiation mainly targets the molecular bonds in the microbial DNA thereby affecting the synthesis of DNA (Ahn and Lee, 2007). Because radiolytic damage cannot be readily repaired, the RNA transcription and protein expression are inhibited. Ionizing of chemical compounds by irradiation also leads to denaturation of enzymes and disruption of cell membrane, resulting in death of microorganisms. γ-Ray, generated by a radioactive isotope (usually cobalt 60), has a high penetration power, thus, can destroy microorganisms both on the surface and in the interior of meat products. γ-Irradiation at a radiation level of 4 kGy significantly reduced the viability of *L. monocytogenes* on beef bologna, and the efficacy was not affected by the presence of antioxidants produced by dextrose-dependent Maillard reaction (Sommers and Fan, 2002). Because the exposure of sugars to irradiation could cause the production of furan, a toxic and potentially carcinogenic compound, the furan concentration in a variety of irradiated RTE meat and poultry products (bologna, frankfurters, beef bologna) was determined (Fan and Sommers, 2006). The result showed that exposures of RTE products to 4.5 kGy radiation at 5°C did not significantly increase the furan levels in most of the treated products. Despite the demonstrated effectiveness against pathogens in RTE meats, γ-irradiation has not been approved for commercial applications on this particular food group.

X-ray, produced by a stream of high-energy electrons produced when fast moving electrons strike on a metal object, emits an ultraviolet light (UV). Sommers et al. (2009) reported that UV (254 nm) irradiation at 1, 2, and 4 J/cm^2 levels resulted in, respectively, 1.31, 1.49, and 1.93-log reductions of *L. monocytogenes* inoculated on the surface of frankfurters that contained 0.07% sodium diacetate and 1.13% potassium lactate. Following an eight-week refrigerated storage, *L. monocytogenes* levels decreased by 0.65 log in non-UV-treated frankfurter packs compared with 2.5 log in the UV-treated packs. The UV treatment up to 4 J/cm^2 had no effect on frankfurter quality (color or texture). The same UV treatment was also effective against other pathogens on RTE frankfurters (Sommers et al., 2010). The combination of UV (0.5 J/cm^2, 100 s) and antimicrobial treatments (0.07% sodium diacetate, 1.13% potassium lactate) produced 1.64, 1.54, and 1.53-log destruction of *L. monocytogenes*, *Staphylococcus aureus*, and *Salmonella* spp., respectively, on the surfaces of frankfurters. Keklik et al. (2009) tested pulsed UV light to inactivate *L. monocytogenes* inoculated on chicken frankfurters. Their study showed up to 1.9-log reductions of the microorganism when the RTE poultry product was treated by UV.

E-beam, also generated by high-energy electrons in an electron accelerator, has been tested for effectiveness to inactivate pathogens in RTE muscle foods. As demonstrated by Foong et al. (2004), E-beam radiation at 1.5 kGy and 2.0 kGy caused 3-log reductions of inoculated *L. monocytogenes* on bologna, roast beef, and turkey, and on frankfurters and hams, respectively. The application of E-beam irradiation at low dosage

levels (< 2.0 kGy) was also an effective treatment to control *L. monocytogenes* contamination on packed RTE ham (Cabeza et al., 2007). Zhu et al. (2009) investigated the effect of the combination of antimicrobial additives and E-bean irradiation on the survival and proliferation of *L. monocytogenes* on cooked turkey breast rolls. They showed that 1.0 kGy or 2.0 kGy irradiation when combined with antimicrobial treatments, for example, 0.1% benzoate and 2% lactate plus 0.1% diacetate, effectively damaged *L. monocytogenes* and completely suppressed the growth of the organism during six weeks of storage at 4°C. Although *L. monocytogenes* present in RTE meats can be significantly affected by irradiation, the fact that it is more resistant to irradiation than *E. coli* O157:H7, *Arcobacter*, *Campylobacter*, *Yersinia*, and *Staphylococcus* (Fu et al., 1995a, 1995b) raises the caution that the efficacy of irradiation in postlethality meat and poultry should always be validated.

High-pressure Treatment

High-pressure processing (HPP) is another emerging and promising technology capable of destroying both spoilage and pathogenic microorganisms on RTE meats. The process includes high-hydrostatic pressure processing, high-hydrodynamic pressure processing, and ultra high-pressure processing. HPP operates by the principle that high-pressure treatments disrupt the bacterial cell membrane (Yaldagard et al., 2008). The leakage of intracellular constituents through the permeabilized cell membrane leads to cell death. The denaturation of key enzymes through protein structural changes is another mechanism by which HPP inactivates microorganisms. For example, membrane bounded ATPase was found to be susceptible to HPP and its inactivation was correlated with cell death (Wouters et al., 1998). A pressure of more than 400 MPa (about 6000 psi) will inactivate vegetative bacteria, including *E. coli*, *Salmonella*, and *Listeria*. In general, vegetative cells are inactivated by pressures at 400–600 MPa, while bacterial spores are more resistant and can survive pressures greater than 1000 MPa (Patterson et al., 1995).

As in-package "cold pasteurization," HHP is particularly attractive for postprocessing treatment for RTE meat products due to its listericidal effect and relatively low impact on the product quality (color, protein denaturation, and water-binding) when compared with its treatment of fresh meat (Campus, 2010) or with postlethality thermal processing. HPP at the levels of 400–900 MPa was shown to improve the shelf-life and microbial safety of cooked ham (Jofré et al., 2008; Marcos et al., 2008) and dry-cured ham (Hereu et al., 2012). The HPP treatments were found to be effective to destroy foodborne pathogens, including *E. coli* O157:H7, *L. monocytogenes, Salmonella spp.*, and *S. aureus*, inoculated on these RTE products.

A substantially improved microbiological stability by HPP makes it a potential nonthermal processing alternative for RTE food safety control during storage. According to Hugas et al. (2002), HPP at 600 MPa for six minutes at 30°C completely destroyed *Salmonella* spp. (initial counts at 3.8 log CFU/g) on cooked ham, and no *Salmonella* was detected on samples stored at 4°C even after 120 days. In a similar study, Aymerich et al. (2005) tested the bacteriocidal effect of HPP at 400 MPa for 10 minutes at 17°C on cooked ham. They noted 2.4 and 1.9-log reductions of *Salmonella* spp. and *L. monocytogenes*, respectively, on the RTE meat stored at 6°C for 42 and 84 days. The application of 500 MPa for five minutes at 18°C was also found to produce a 2-log reduction of *L. monocytogenes* inoculated on sliced beef and cured ham after storage at 6°C for 210 days (Rubio et al., 2007).

Despite its efficacy to destroy microorganism, HPP may have an undesirable consequence for the palatability of treated RTE products, depending on the product type. Rivas-Cañedo et al. (2012) analyzed the impact of HPP (400 MPa, 10 min) on the flavor profile of low-acid fermented sausages and noticed no appreciable changes in oxidative stability, color, and flavor attributes of treated products. However, the reduced abundance of desirable flavor compounds generated during refrigerated storage in HPP-treated sausages due to the inactivation of volatile-producing microorganisms could lead to a less characteristic meat product. A similar conclusion was drawn by Rubio et al. (2007) who applied 500 MPa for five minutes to process dry-cured beef. Clariana et al. (2011) reported that HPP at 400 MPa for six minutes only slightly increased lightness of sliced skin vacuum-packed dry-cured ham. However, treatment with 900 MPa for 10 minutes markedly modified the color of commercial dry-cured ham, and the sensory attributes were also altered as indicated by the increased hardness, chewiness, brightness, and saltiness. The negative effects of HPP appeared to be related, in part, to the temperature increase during the pressure treatment. For example, the initial temperature (12°C) of the products rose to 46–52°C for the 900 MPa treatment (Clariana et al., 2011).

The efficacy of microbial inactivation is influenced by a number of factors. For example, the pressure resistance of microorganisms is reinforced in nutrient-rich media (Hoover et al., 1989). Hence, proteins and lipids present in the broth of RTE meat products could have a protective effect on microbial contaminants. Furthermore, sublethally injured cells from HPP have been shown to recover during storage and grow, producing high levels of biogenic amines (tyramine and histamine, directly, or putrescine and cadaverine, indirectly) (Ruiz-Capillas et al., 2004). Therefore, more in-depth studies are needed to determine how different HPP factors can affect the recovery of microbial cells as well the negative impact on the product quality.

ANTIMICROBIAL ADDITIVES

An antimicrobial agent is a substance that has the effect of inhibiting growth (bacteriostatic) or causing death (bacteriocidal) of microorganisms, including pathogens such as *L.*

monocytogenes and *Salmonella*, throughout a product's shelf-life. A comprehensive list of antimicrobials and treatments permitted for use in RTE meat and poultry products can be found in *Safe and Suitable Ingredients Used In The Production Of Meat And Poultry Products* (FSIS, 2009). The use of antimicrobials as additives to control pathogens in RTE meats is considered a novel approach to food safety. Table 1 lists some common additives that prove to be effective against *L. monocytogenes*. They can be applied to RTE meats either by direct incorporation as product formulation ingredients or by spray on the product surface before packaging. Antimicrobial ingredients at the application levels allowed must be validated for their effectiveness to inhibit the growth of *L. monocytogenes* by 1 to 2 log through the duration of the shelf-life of an RTE product.

Organic Acids

A variety of carboxylic acids and their salts are applied to control pathogens in RTE meats. Among them, lactic acid and diacetic acid are common antilisteria compounds (Table 1). For improved solubility over a wide range of pH, their salts–sodium lactate and sodium diacetate—are used instead (Barmpalia et al., 2004). Other acids showing antimicrobial activity include sorbic acid, benzoic acid, and propionic acid. The application of organic acids as antimicrobials to control pathogens in RTE meat and poultry is simple and cost-effective.

Sodium diacetate, also called sodium acetoacetate, is a compound with the formula $CH_3C(O)CH_2CO_2Na$. Because the most effective microbial inhibitory effect is achieved when sodium diacetate is combined with sodium lactate (Bangel, 2012), these two salts (or acids) are generally applied together in commercial RTE meat and poultry products, such as packaged luncheon meat slices, wieners, smoked-cooked ham, light bologna, and cotto salami (Seman et al., 2002). Common combinations are 0.125–0.25% sodium diacetate with 1.5–3% sodium/potassium lactate (Thompson et al., 2008). As stipulated by FSIS, the maximum permissible levels of sodium diacetate and lactate used in RTE meats are 4.8% and 0.25%, respectively.

The combination of 1.6% sodium lactate and 0.1% sodium diacetate was found effective in inhibiting the growth of *L. monocytogenes* inoculated on cured ham slices that were stored at 4°C up to 12 weeks (Glass et al., 2007). Frankfurters formulated with 2% and 3% potassium lactate had 5.1 and 5.4-log reductions in *L. monocytogenes* population after storage at 10°C for 60 days when compared with the control (Porto et al., 2002). Samelis et al. (2002) found that 1.8% sodium lactate used alone in frankfurter formulations inhibited the growth of *L. monocytogenes* for 50 days, but when combined with 0.25% sodium diacetate at a pH below 7.0, *L. monocytogenes* was inhibited throughout 120 days of refrigerated storage.

Sodium levulinate (4-oxopentanoic acid), a 5-carbon organic acid that has a generally recognized as safe (GRAS) status, is another effective organic antimicrobial. It is used as a flavoring agent in many food applications. Levulinate has been shown to inhibit the growth of *L. monocytogenes* in cooked turkey roll and bologna more efficiently than sodium lactate and the combination of sodium lactate (1.875%) and sodium diacetate (0.125%) (Thompson et al., 2008), which is a standard industry application to control the safety of refrigerated RTE meats. Addition of 2% or more sodium levulinate to turkey roll and 1% or more sodium levulinate to bologna completely prevented growth of *L. monocytogenes* during 12 weeks of refrigerated storage. Furthermore, the addition of sodium levulinate as an antimicrobial in the formulation did not alter the flavor profile of turkey breast roll or bologna when compared to the control (Thompson et al., 2008).

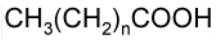
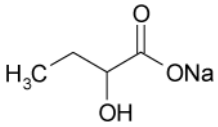
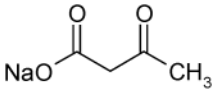
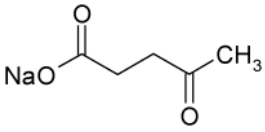
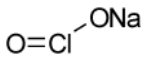
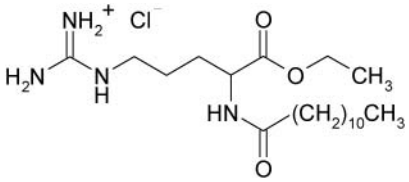
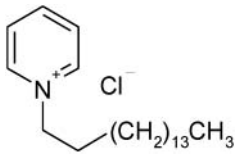
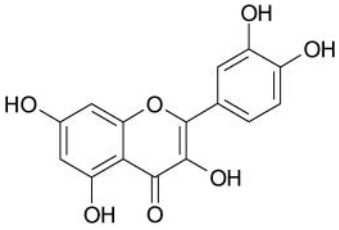
The mechanism by which organic acids inhibit bacterial pathogens appears to involve the passage of the undissociated form of the acids across the cell membrane (Russell, 1992). Once arriving in the cytosol, the acids dissociate because the cell interior has a higher pH than the exterior. Protons generated from the dissociation of the organic acids then acidify the cytoplasm, resulting in the inactivation of critical cellular functions (e.g., enzyme activity) due to low intracellular pH. The removal of excess protons is energy dependent; the depletion of cellular energy sources would impair the cell growth (Shelef, 1994). The ability of lactic acid to inhibit *L. monocytogenes* and other pathogenic and spoilage microorganisms can also be understood considering that lactic acid-producing bacteria can thrive in acidic environments and strongly compete against undesirable microorganisms in food systems through generating bacteriocins and hydrogen peroxide (Lindgren and Dobrogosz, 1990; Breidt and Bleming, 1998). The mechanism of action for the salts of organic acids is thought to be somewhat different from that of the acids. For example, it has been suggested that high levels of lactate ion may shift the pyruvate reduction-to-lactate reaction closer to its thermodynamic equilibrium, thereby inhibiting the anaerobic energy metabolism pathway essential for the cell growth (Maas et al., 1989). On the other hand, sodium levulinate is thought to inhibit microbial growth through its prooxidative effect (Yi and Kim, 1982).

The antilisteria effect of organic acids or their salts is accentuated by the presence of sodium chloride and nitrite. Therefore, organic acids are generally more effective in cured meats, such as ham, frankfurters, and bologna, than in non-cured products (Palumbo and Williams, 1994; Houtsma et al., 1996). The temperature appears to be involved in the mechanism of antilisteria because *L. monocytogenes* grown at 7°C shows reduced acid survival and an altered transcriptional response to acid shock compared to *L. monocytogenes* grown at 37°C (Ivy et al., 2012).

Bacteriocins

Bacteriocins are peptides produced by bacteria that function as antibiotics to inhibit the growth of similar or closely related

Table 1 Common and potential antimicrobial agents for controlling pathogens in RTE meat and poultry products

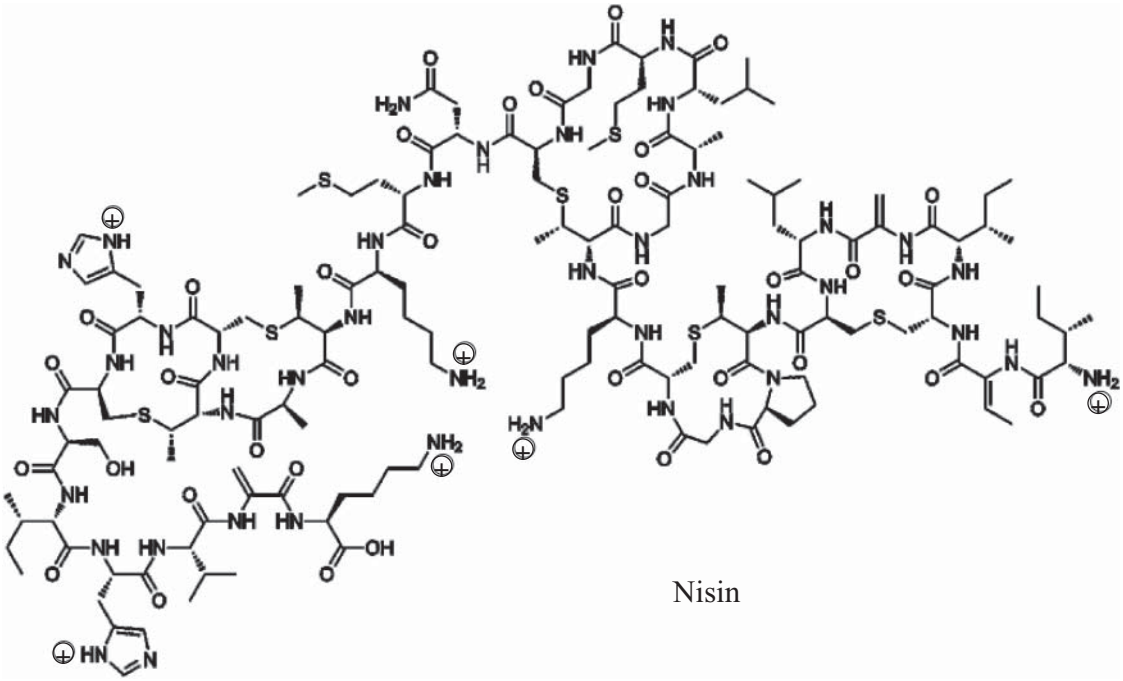
Name	Structure	Mode of action	Reference
Organic acids		Acidifying cytoplasm to disrupt cellular metabolism	Russell, 1992
Sodium (or potassium) lactate		Reducing water activity; inhibiting anaerobic metabolism	Maas et al., 1989; De Wit and Rombouts, 1990; Ita and Hutkins, 1991
Sodium (or potassium) diacetate		Reducing water activity; interfering with metabolic activity	De Wit and Rombouts, 1990; Brul and Coote, 1999
Sodium levulinate		Prooxidative effect	Yi and Kim, 1982
Nisin	Cyclic peptide containing 34 amino acids (3354 Da)	Dissipation of proton motive force; disruption of cell membrane	Montville and Bruno, 1994
Pediocin PA1	Peptide containing 44 amino acids (4629 Da)	Dissipation of proton motive force; disruption of cell membrane	Montville and Bruno, 1994
Enterocins	Peptides, 3000–8000 Da	Dissipation of proton motive force; disruption of cell membrane	Montville and Bruno, 1994
Acidified sodium chlorite		Disruption of protein synthesis via oxidation of sulfhydryls and nucleotides by chlorine dioxide	Warf and Kemp, 2001
Lauric arginine ester		Targeting cell membrane; formation of mesosome-like structures and void areas in the cytoplasm	Infante et al., 1985; Rodríguez et al., 2004
Cetylpyridinium chloride		Binding with membrane proteins and lipids; lysis of cell wall; degradation of enzymes and nucleic acids	Salton, 1968; Russell, 2002
Lactoferrin	Glycoprotein, 80,000 Da	Binding to lipopolysaccharide of bacterial cell wall where lactoferrin-bound iron oxidizes bacteria via the formation of peroxides	Farnaud and Evans, 2003
Herb extracts	Various phenolic compounds, such as quercetin: 	Binding to cell wall and cytosolic components to interfere with cell metabolism; inhibits ATP synthesis	Vattem et al., 2005; Nohynek et al., 2006

bacterial strains. In essence, they are produced to defend the host cells. Many bacteriocins are produced by lactic acid bacteria (LAB) through the fermentation process. Bacteriocins are generally small peptides consisting of 30 to 60 amino acids. They are cationic, hence, have a high isoelectric point and are amphiphilic due to the presence of regions within the molecule that are predominantly hydrophilic or hydrophobic.

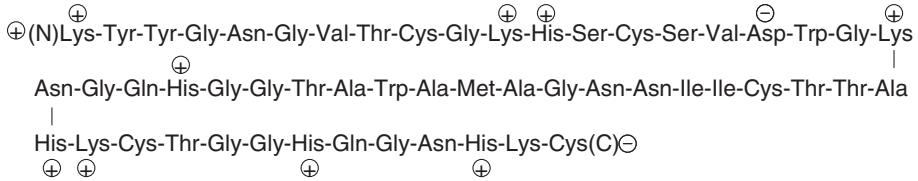
A variety of mechanisms have been proposed to explain the bacteriocidal effects of bacteriocins. The permeabilization of the cytoplasmic membrane followed by leakage of cellular compounds, damage of DNA and RNA, and inhibition of protein synthesis are the most widely accepted (Konisky, 1982; Bhunia et al., 1991; Fimland et al., 2005). Nisin, for example, can form a complex with Lipid II, a cell wall and peptidoglycan precursor, to generate pores allowing leakage of intracellular constituents (Breukink and de Kruijff, 1999). A unified hypothesis supporting the apoptosis of cells is that bacteriocins act by the depletion of proton motive force (Montville and Bruno, 1994).

In general, bacteriocins are heat resistant, but they are inactivated by proteolytic enzymes such as trypsin, pepsin, and other proteases. The use of LAB to produce bacteriocins offers other advantages, such as exerting probiotic properties (Vandenberg, 1993; Castro et al., 2011). Nisin, pediocin, and enterocins are some of the best characterized bacteriocins that are effective to control pathogens, such as *L. monocytogenes*, *C. tyrobutyricum*, and *S. aureus*, in RTE meat and poultry products (Rodriguez et al., 2002; Kouakou et al., 2008; Rehaiem et al., 2010).

Nisin. Nisin is produced by the fermentation with *Lactococcus lactis*, a GRAS microorganism. It is a polycyclic peptide with 34 amino acid residues (molecular mass 3354 Da). Nisin contains the uncommon amino acids lanthionine, methyllanthionine, didehydroalanine, and didehydroaminobutyric acid. Furthermore, nisin is abundant in lysine, histidine, valine, leucine, and isoleucine and is devoid of negatively charged amino acids (Figure 1). This unique structure renders nisin a high affinity for cell membrane. The antibacterial activity of nisin



Nisin



Pediocin PA1

Figure 1 Primary structure of bacterial nisin and pediocin PA1.

is attributed to its interaction with anionic phospholipids in the bacterial cell wall resulting in the disruption of normal membrane function and leakage of cellular components (Breukink et al., 1997; Juneja, 2012). Nisin is effective against many gram-negative bacteria, including *L. monocytogenes*, hence, is particularly attractive for improving the safety of RTE meats (Martin-Visscher et al. 2011).

Nisin can be added directly to meat product formulations or incorporated into the packaging materials. When used in the product formation at 1.25–6.25 mg/kg or in the dipping solution at a concentration of 5.0–25.0 mg/L, nisin significantly prolonged the shelf-life of cooked sausage stored at 6–12°C (Delves-Broughton, 2005). A study determined pH, anti-*Listeria*, and general antimicrobial properties of nisin on RTE vacuum-packaged turkey ham (Ruiz et al., 2010). Four-log reductions were observed on day 0 and day 7 for a 0.4% nisin treatment when compared with the positive control. *L. monocytogenes* counts decreased from 4.97 log CFU/g on day 0 and remained less than 2 log CFU/g through 63 days of refrigerated storage for the 0.5% nisin treatment. The antimicrobial activity of a grape seed extract when combined with bacteriocins like nisin has demonstrated greater effectiveness than when used alone against *L. monocytogenes* (Sivarooban et al., 2008). This may be due to the synergistic mechanism of action of nisin and polyphenols present in the grape seed extract.

Another study investigated the efficacy of in-package heat pasteurization combined with presurface application of nisin and/or lysozyme to reduce and prevent the subsequent recovery and growth of *L. monocytogenes* during refrigerated storage of low-fat turkey bologna (Mangalassary et al., 2008). The nisin-lysozyme treatment resulted in an additional reduction of 1.4 log CFU/cm^2 in *L. monocytogenes* population immediately after pasteurization when compared with the control meats. There was an additive inhibitory effect of nisin and lysozyme during storage; by three weeks, *L. monocytogenes* population was reduced to an undetectable low level.

Pediocin. A small peptide produced by *Pediococcus acidilactici*, also a GRAS organism used in fermented foods, pediocin is another strong antimicrobial. Pediocin is made up of 44 amino acid residues (molecular mass 4629 Da) (Henderson et al., 1992), which has a well-conserved hydrophilic *N* terminus. Similar to nisin, pediocin is a positively charged basic peptide (Figure 1). Pediocin AcH has been proven to be effective against both spoilage and pathogenic organisms, including *L. monocytogenes*, *Enterococcus faecalis*, *S. aureus*, and *C. perfringens* (Bhunia et al., 1988). Pediocin is thermostable and is bacteriocidal over a wide range of pH. The combined effect of pediocin (3000 and 6000 AU) with postpackaging pasteurization (71, 81, and 96°C) on frankfurters during storage at 4, 10, and 25°C for 12 weeks was studied. The result showed no increase in *L. monocytogenes* populations up to 7 weeks for the combined treatment at any of the temperatures tested; however, after 7 weeks, populations increased by 2 to 3 log CFU/g for most samples (Chen et al., 2004).

Enterocins. Also referred to as enterococcal bacteriocins, enterocins encompass a group of peptides (molecular mass 3000–8000 Da) produced by *Enterococcus* spp. They are active against gram-positive foodborne pathogens, including *L. monocytogenes*, *S. aureus*, and *Bacillus cereus* (Jack et al., 1995; Cleveland et al., 2001). Enterocins A and B when applied to cooked ham, pate, and frankfurters significantly inhibited the growth of *L. monocytogenes* inoculated on the products (Aymerich et al., 2000). Other enterocins have also been shown to suppress the growth of *L. monocytogenes* on RTE meats, for example, on dry fermented salami by enterocin CCM 4231 (Lauková et al., 1999) and on sausage (Ananou et al., 2005a, 2005b) and cooked ham (Baños et al., 2012) by enterocin AS-48.

Acidified Sodium Chlorite

Acidified sodium chlorite ($NaClO_2$) is a widely used antimicrobial agent. The antimicrobial activity is attributed to the oxidative effect of chlorous acid, which is derived from the conversion of chlorite ion into its acid form under acidic conditions. Specifically, chlorous acid ($HClO_2$) produced from the acidification of chlorite gradually decomposes to form chlorate ion, chloride ion, and chlorine dioxide (ClO_2), an oxidizing compound.

$$NaClO_2 + H^+ \rightarrow HClO_2 + Na^+$$
$$HClO_2 \rightarrow ClO_2 + \ldots.$$

The reactions happen instantly on mixing sodium chlorite with an acid (e.g., citric acid), therefore, the antibacterial solution needs to be prepared right before use. The uncharged chlorous acid will penetrate through bacterial cell walls and disrupt protein synthesis by virtue of its reaction with protein sulfhydryl groups and disulfide as well as nucleotides (Warf and Kemp, 2001).

Acidified sodium chlorite is approved as a food additive by both USDA and FDA for use on meat, poultry, seafood, and fruits and vegetables, and also approved by EPA as a pesticide for use on food-contact surfaces. Beverly et al. (2006) found that when treated with acidified sodium chlorite at concentrations no less than 500 ppm, spicy roast beef and regular roast beef samples had more than 4.0 and 2.5 log CFU/g reductions in *L. monocytogenes* populations, respectively, compared with untreated samples. However, Luchansky et al. (2006) reported that hot water postprocess pasteurization alone was effective in reducing *L. monocytogenes* on the surface of cook-in-bag turkey breasts, while potassium lactate-sodium diacetate solution (1.54%) and acidified sodium chlorite (0.11%) were only somewhat effective at controlling the subsequent growth of this pathogen during refrigerated storage. Lim and Mustapha (2007) found that spray treatment of sliced roast beef with 0.5% cetylpyridinium chloride totally inhibited *L.*

monocytogenes to an undetectable level (< 1 log CFU/cm^2) throughout the entire storage (up to 10 days). The same cetylpyridinium chloride spray also totally inhibited *S. aureus* on day 0 but this strain slowly recovered from day 2 (0.2 log CFU/cm^2) to day 10 (3.11 log CFU/cm^2).

Lauric Arginate

Lauric arginate or lauric arginine ester (LAE), chemically expressed as ethyl-*Nα*-lauroyl-*L*-arginate•HCl, is an FDA-approved antimicrobial that can be used to inactivate and inhibit the growth of foodborne pathogens on RTE products during refrigerated storage. LAE is synthesized by reacting arginine with ethanol and lauric acid, all naturally occurring substances (Contijoch et al., 2003; Bakal and Diaz, 2005). LAE is readily metabolized when consumed, hence, has been granted a GRAS status by FDA.

Lauric arginate has been found to exert in-package lethality and suppress pathogen growth in RTE meats at 4°C (Luchansky et al., 2005, 2007). The antimicrobial mechanism of LAE is unclear, although it is believed to be able to interact with bacterial membrane, resulting in the formation of mesosome-like structures and void areas in the cytoplasm (Infante et al., 1985; Rodríguez et al., 2004). The cationic nature seems to be a factor in the antimicrobial effect, just like bacteriocins.

According to Brandt et al. (2010), LAE at 12.50 mg/kg was the minimum inhibitory concentration against *L. monocytogenes* when tested with a broth dilution method. Using the Sprayed Lethality in Container method, Porto-Fett et al. (2010) delivered different volumes and concentrations of LAE to the surfaces of RET meats to control *L. monocytogenes*. The result showed that the application of 4 mL of LAE at concentrations as low as 22 mg/kg onto the surface of frankfurters (8 links/package) previously inoculated with *L. monocytogenes* (3.3 log CFU/package) produced an immediate reduction of *L. monocytogenes* by 1.8 log. However, additional antimicrobial were required to achieve a total suppression of subsequent growth at 4°C. A variety of supplemental antimicrobials have been studied in conjunction with LAE, including lactate and diacetate, nisin, acidic calcium sulfate, and ε-poly-*L*-lysine (Luchansky et al., 2005; Martin et al., 2009). Porto-Fett et al. (2010) reported that, while LAE inactivated *L. monocytogenes* on frankfurter surfaces by 1–2 log units, the foodborne pathogen was able to recover and proliferate to approximately 7 log CFU/g during long-term refrigerated storage at 4°C. This outcome was substantially reduced when LAE (22 or 44 mg/kg) was combined with sodium diacetate (0.097% or 0.19%) and potassium lactate (0.68% or 1.36%).

The use of LAE in combination with flash pasteurization (short pulses of steam at 120°C for 1.5 seconds) was found to be an effective hurdle process for decontamination of frankfurter surfaces (Sommers, 2012) because it significantly inhibited *Listeria* while not affecting the product color and texture. Postlethality pasteurization with steam (120°C) for 1.5 seconds, when combined with LAE (3.33 mL of a 5% v/v solution per pack of four frankfurters), resulted in 3.3-log reductions of *L. innocua* (used as a nonpathogenic surrogate for *L. monocytogenes*) that was surface-inoculated onto frankfurters.

Cetylpyridinium Chloride

Cetylpyridinium chloride (CPC), a quaternary ammonium compound, has been approved by the USDA and FDA to treat raw poultry carcasses. It is also an active ingredient in some mouthwashes. CPC has been applied as a dip or spray to fresh poultry (Breen et al., 1997) and fresh beef (Cutter et al., 2000) to effectively control pathogens, including *E. coli* O157:H7, *Salmonella* spp., and *Listeria* spp. CPC, under the brand name "Cecure," and is highly effective against *Salmonella*, *E. coli*, *Campylobacter*, *Listeria*, and *Staphylococcus* in RTE meat products.

CPC is an emerging antimicrobial awaiting the approval as a potential decontaminating agent for RTE meats. Treatment of *L. monocytogenes*-inoculated slices and surface of roast beef with 1% CPC solution resulted in 2–4 log CFU/cm^2 reductions of the pathogen and significantly inhibited its growth during subsequent refrigerated storage up to 6 weeks (Singh et al., 2005a). In another study, Singh et al. (2005b) inoculated Polish sausage with *L. monocytogenes* at either low (3 log CFU/g) or high (7 log CFU/g) levels, followed by treating with a 1% CPC spray, vacuum packaged, and stored for 42 days at 0 or 4°C. At the high inoculation level, *L. monocytogenes* populations were reduced by 3 log CFU/g immediately after treatment and, after 42 days of refrigerated storage in vacuum, the populations on treated samples were 4 log CFU/g lower than nontreated samples. The product quality was not significantly affected by the antimicrobial treatments.

The mechanism of CPC against *L. monocytogenes* is not clear. However, the following general antimicrobial actions of CPC have been proposed: (1) adsorption and penetration of cell wall, (2) disruption of cytoplasmic membrane due to interaction with membrane lipids and proteins, (3) leakage of intracellular low molecular-weight constituents, (4) degradation of proteins and nucleic acids, and (5) cell lysis due to wall-degrading autolytic enzymes (Salton, 1968; Russell, 2002).

Lactoferrin

Lactoferrin is an iron-binding glycoprotein with a molecular mass of about 80,000 Da. It is commonly isolated from cow milk and can be produced through recombinant technology. The strong antimicrobial activity of lactoferrin has been explained by its ability to bind to lipopolysaccharide of the bacterial cell wall where the iron bound by lactoferrin oxidizes

bacteria via the formation of peroxides. This leads to the disruption of the cell and results in the cell death (Farnaud and Evans, 2003). As a component of the innate immune system, lactoferrin also exerts antiviral, antifungal, antiinflammatory, and anticancer activity.

A study was conducted to evaluate the antilisterial effect of lactoferrin as a formulation ingredient or as surface treatment in comparison with organic acids and salts on various RTE meat products (Barmpalia-Davis, 2008). It was shown that lactoferrin at a 0.5% product formulation level reduced the growth of inoculated *L. monocytogenes* on bologna by 2 log CFU/cm^2 during storage at 4°C up to three months. The combination of 0.5% lactoferrin and 1.8% potassium lactate proved to be most effective as it generated a 5-log reduction of *L. monocytogenes* during the first 45 days of storage. Interestingly, no obvious *L. monocytogenes* population reduction was observed with 1% lactoferrin alone and surprisingly, a stimulated *L. monocytogenes* growth was found with the 0.5% lactoferrin and 0.125% diacetate combination treatment. The cause for the latter effect was not clear.

Spices and Herbs

Plant-derived spices and herbs are widely used as flavoring agents in food and, in some cultures, as medicinal materials. Many plant extracts also possess antimicrobial activity and are effective against pathogens. Among them are cassia, clove, garlic, sage, oregano, pimento, thyme, rosemary, *scutellaria*, and *forsythia suspensa* (Thunb) (Farag et al., 1989; Hao et al., 1998; Kong et al., 2007). Clove oil, with eugenol being an active component, is capable of inhibiting *L. monocytogenes*, *Salmonella Enteritidis*, *E. coli*, and *S. aureus* (Cressy et al., 2003; Mytle et al., 2006). Oussalah et al. (2007) evaluated 28 essential oils for their antibacterial properties, noting that most provided an effective control against *E. coli* O157:H7, *L. monocytogenes*, *Salmonella*, and *Staphylococcus*.

Zhang et al. (2009) screened 14 spice extracts for antimicrobial activity against *L. monocytogenes* and the spoilage bacteria *E. coli*, *P. fluorescens*, and *Lactobacillus sake*. The extracts of clove, rosemary, cassia bark, and licorice were found to contain strong antimicrobial activity, but the mixture of rosemary and liquorice extracts was the most effective. When 2.5, 5, and 10 mg/mL of the mixed rosemary/licorice extracts were spray-applied to RTE ham slices inoculated with *L. monocytogenes*, the growth of this pathogen on vacuum-packaged ham over 28 days of storage at 4°C was reduced by 2.5, 2.6, and 3 log CFU/cm^2. Singh et al. (2003) investigated the efficacy of plant essential oils to inhibit *L. monocytogenes* in RTE meats. The application of 1 mL/L thyme oil or clove oil to the surface of inoculated frankfurters resulted in significant reductions of *L. monocytogenes* on hotdogs containing minimal or low amounts of fat.

The antimicrobial effects of plant extracts are generally attributed to phenolic compounds, which include flavonoids, phenolic acids, lignans, and polymeric tannins (Cushnie and Lamb, 2005; Moreno et al., 2006; Cueva et al., 2010). Several common antimicrobial polyphenols are displayed in Figure 2. These compounds are able to bind and penetrate bacterial cell membrane generating pores that increase the permeability, especially for gram-positive pathogens such as *L. monocytogenes*. It has also been reported that polyphenols can disintegrate outer membrane of gram-negative bacteria causing leakage of cellular components (Nohynek et al., 2006). For phenolic acids, such as benzoic acid, the antimicrobial action against pathogens has been explained by hyperacidification at the plasma membrane interphase, which alters cell membrane potential, changes its permeability, and affects the Na^+/K^+

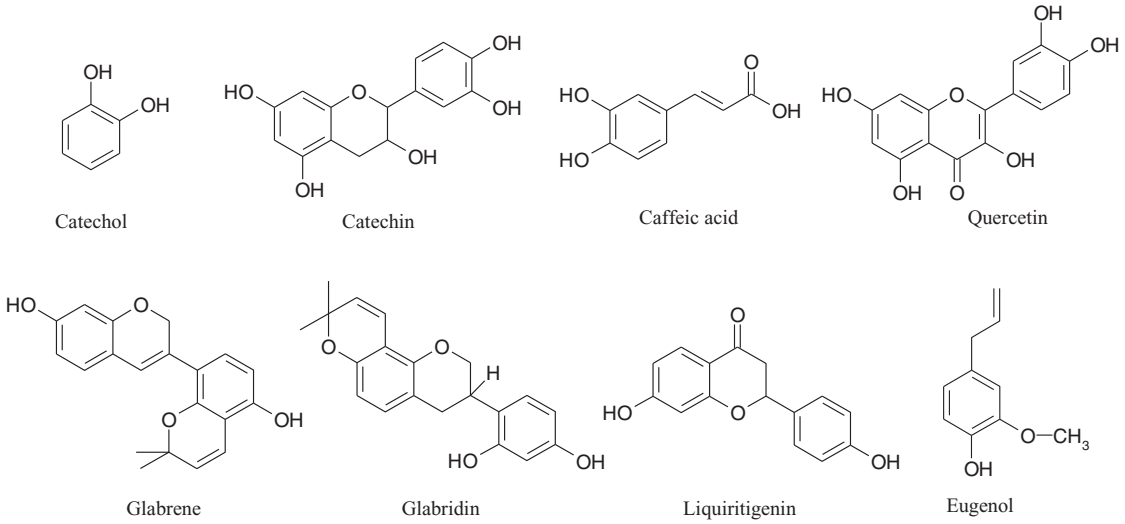


Figure 2 Common phenolic antimicrobials present in plant extracts.

ATPase pump implicated in ATP synthesis (Vattem et al., 2005).

Other Antimicrobials Approved for RTE Products

In addition to the above additives that have been approved or under evaluation by the USDA or FDA, a number of other chemicals have been granted the GRAS status to control foodborne disease agents in RTE meat and poultry products, which are listed in FSIS (2009).

Egg white lysozyme: applied 2.5 mg per pound in the finished product when used in casings; 2.0 mg per pound on cooked meat and poultry products.

Hops beta acids: applied 2.5 mg per pound in the finished product when used in casings; 2.0 mg per pound on cooked meat and poultry products.

Lactic acid bacteria (a mixture consisting of *L. acidophilus*, *L. lactis*, and *L. acidilactici*): applied by dipping product into a solution containing 1×10^7 CFU/g. LAB species can produce a variety of metabolites, such as lactic acid (which lowers the pH), hydrogen peroxide, and bacteriocins to competitively inhibit pathogens (Vandenberg, 1993).

Carnobacterium maltaromaticum strain CB1: applied as a spray to meat products at a maximum concentration (at inoculation) of 1×10^4 CFU/g.

Bacteriophage preparation (a mixture of equal proportions of six different individually purified lytic-type bacteriophages specific against *L. monocytogenes*): applied as a spray at a level not to exceed 1 mL of the additive per 500 cm^2 product surface area; or applied to the surface of the product to achieve a level of 1×10^7 to 1×10^9 PFU/g.

Sodium metasilicate: up to a 6% solution applied to the surface of the product at a rate not to exceed 300 ppm of the finished products (FSIS, 2012).

ANTIMICROBIAL PACKAGING

Active packaging with antimicrobials imbedded in or coated on the film or package sheet is an emerging technology for the control of pathogen growth in RTE meat and poultry products. Because microbial contamination is most likely on the meat product surface, the application of antimicrobial film is of particular attractiveness. Moreover, antimicrobial-containing films avoid the risks of potentially negative interaction with the food components and can provide longer preservation compared with the conventional addition of antimicrobials (e.g., enterocins) directly into food (Quintavalla and Vicini, 2002). Both inedible and edible packaging materials such as films are made as carriers for antimicrobial agents. Ideally, antimicrobials that are incorporated in the packaging material are slowly released onto food to provide a sustained protection of the meat products. It has been shown that plastic bags coated with a pediocin powder completely inhibited the growth of inoculated *L. monocytogenes* on cooked ham through 12 weeks of storage at 4°C (Ming et al., 1997). In contrast, the *Listeria* population in nontreated ham increased 1.5 log after 12 weeks. Limjaroen et al. (2005) reported that the application of polyvinylidene chloride films containing up to 3% sorbic acid between slices of beef bologna inhibited the growth of *L. monocytogenes* by 7.1 log after 28 days of storage at 4°C.

Cagri et al. (2003) investigated the effect of whey protein edible casings containing 1% *p*-aminobenzoic acid on the inhibition of surface-inoculated *L. monocytogenes* (10^3 CUF/g) on frankfurters. The result showed a 2.5-log increase of *L. monocytogenes* in control samples with whey protein coating but no growth on products with the antimicrobial-treated whey protein coating after 42 days of refrigerated storage.

Chitosan is widely considered to be an antimicrobial material. However, chitosan-coated plastic films were found to be ineffective to control the growth of inoculated *L. monocytogenes* on the surface of cooked hams (Ye et al., 2008). On the other hand, when ham slices inoculated with *L. monocytogenes* were packaged in chitosan-coated plastic films that also contained nisin (500 IU/cm^2), sodium lactate (0.01 g/cm^2), sodium diacetate (0.0025 g/cm^2), potassium sorbate (0.003 g/cm^2), or sodium benzoate (0.001 g/cm^2), the growth of *L. monocytogenes* during storage was significantly inhibited. Most notably, chitosan-coated plastic films containing 0.001 g/cm^2 sodium lactate totally inhibited *L. monocytogenes* on ham samples stored at 4°C for 12 weeks.

A polylactic acid-based film, in which 5–15% lactic acid and 10–30% sodium lactate were incorporated by the extrusion film-blowing process, was tested for antimicrobial activity against *E. coli* O157:H7, *L. monocytogenes*, and *Salmonella enterica serovar typhimurium* (Theinsathid et al., 2001). The result showed that antimicrobial film incorporated with lactic acid was highly effective in inhibiting *L. monocytogenes* but not inhibitory of *E. coli O157:H7* and *S. typhimurium*. The ability to inhibit *Listeria* suggests the feasibility of this bioactive film for the protection of RTE meats. In a follow-up study (Theinsathid et al., 2012), when a lauric polylactic acid (PLA) film coated with 0.07% LAE was used as a package for cooked sliced ham, the inoculated *L. monocytogenes* and *Salmonella enterica S. typhimurium* showed 2–3 log reductions after 7 days of storage.

Min et al. (2005) applied whey protein films or coatings containing lysozyme to inhibit *L. monocytogenes* in a smoked salmon product. WPI films incorporated with 204 mg of lysozyme per gram of film (dry basis) inhibited the growth of *L. monocytogenes* on the smoked salmon by 4.4 log CFU/cm^2 during storage at 4 or 10°C up to 35 days. WPI coatings prepared with 25 mg of lysozyme per gram of coating solution also imparted a 2.4-log initial reduction of the *L. monocytogenes* population. Overall, the incorporation of lysozyme in WPI films and coatings was more effective than direct application of lysozyme to smoked salmon surfaces. Marcos et al. (2007) also investigated antimicrobial effects of biodegradable films (alginate, zein, and polyvinyl alcohol) containing 2000

AU/cm^2 of enterocins against *L. monocytogenes* inoculated on sliced cooked ham, reporting significant inhibitions (up to 2 log CFU/g reductions) of the microorganism when compared with control on both vacuum and nonvacuum packaged products stored at 6°C for 28 days. In another study, enterocin 416K1, produced by *E. casseliflavus* IM 416K1, was coated on a LDPE (low density polyethylene) film (Iseppi et al., 2008). This bioactive film effectively inhibited *L. monocytogenes* NCTC 10888, showing an average of 1-log reduction of the pathogen artificially inoculated on frankfurters when stored at 4°C for up to 28 days.

The atmosphere in which RTE meats are packaged can affect the survival of *L. monocytogenes*. As reported by Uppal et al. (2012), the population of *L. monocytogenes* inoculated on the surface of kippered beef steak and turkey tenders was reduced by more than 1-log cycle after 24-hour storage when packaged in vacuum, a heat-sealed package, or a N2-flushed package containing oxygen scavenger. It was recommended that processors should hold products packaged under these conditions a minimum of 72 hours to enhance the margin of safety for *L. monocytogenes* control.

CONCLUSIONS

Read-to-eat meat and poultry products as a unique group of convenient, palatable, and nutritious muscle foods have become an icon in the modern society where work and life tend to have a fast pace and the demand for food that can be efficiently consumed is accordingly high. However, susceptibilities of RTE products to microbial contamination and growth predispose consumers to real health risks. The above review has presented the latest research and briefly discussed the current intervention technologies and their mode of actions to control the growth of *L. monocytogenes*. Because of the pervasive nature of *L. monocytogenes*, the long shelf-life of RTE meats, and often the lack of proper handling and care of such products by consumers, the food industry constantly strives to improve existing technologies and develop new hurdle strategies to minimize the outbreak associated with RTE products. At the present, the combination of antimicrobial agents and post-package pasteurization seems to be the most effective and economically feasible intervention technology. Yet, the use of active packaging materials that are incorporated with antimicrobials, including lactate, diacetate, bacteriocins, acidified sodium chlorite, lauric arginate, and plant-derived antimicrobial extracts, for controlled antimicrobial release and sustained food protection appears to be gaining the momentum. Continuing efforts in this important and dynamic research field are critical because only through such endeavors will a strong scientific basis be established for the development of effective new hurdle technologies as well as pertinent regulatory guidelines to ensure the safest possible supply of RTE products.

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