

Postharvest intervention technologies for safety enhancement of meat and meat based products; a critical review

Muhammad Sohaib¹ · Faqir Muhammad Anjum² · Muhammad Sajid Arshad² · Ubaid Ur Rahman¹

Revised: 19 July 2015 / Accepted: 28 July 2015 / Published online: 25 September 2015
© Association of Food Scientists & Technologists (India) 2015

Abstract Globally, the demand for safe, healthy and nutritious meat and allied products possesses improved taste with extended shelf life is mounting. Microbial safety is among the imperative challenges that prevails in meat products because they provide an ideal medium for the growth of microorganisms particularly pathogenic bacteria. The incidence of these microbes can result quality deterioration of products leading towards food borne diseases when consumed by peoples. Several preservation technologies like chemical and biological interventions are effective to retard or inactivate the growth of micro-organisms most commonly related to food-borne diseases. Despite these, innovative approaches like hydrostatic pressure processing, active packaging, pulse electric field, hurdle approach and use of natural antimicrobials can be deployed to enhance the safety of meat and meat products. The objective of review is to describe the current approaches and developing technologies for enhancing safety of meat and allied meat products.

Keywords Food safety · Intervention technologies · Organic acid · Irradiation · Ozone · HPP · Essential oils

✉ Muhammad Sohaib
ftsohaib@yahoo.com

¹ National Institute of Food Science and Technology, University of Agriculture, Faisalabad, Pakistan

² Institute of Home and Food Sciences, Government College University, Faisalabad, Pakistan

Introduction

The account of Food borne illnesses are estimated about 5 million reported cases that lead towards 60,000 hospitalizations and 1800 deaths eventually and about half of food borne outbreaks are linked to the consumption of contaminated meat (CDC 2010). In the European Union (EU), during 2009, a total of 5550 foodborne outbreaks were reported that involved 48,984 people, resulting in 4356 hospitalizations and 46 deaths (EFSA 2011). Now a days, particularly in developed countries consumer demand safe and healthy meat containing natural ingredients to enhance its shelf life is mainly linked with consumers increased knowledge about safe food (Aymerich et al. 2008). Predominantly, there is mounting demand for meat products containing lesser salt content due to onset of hypertension and high blood pressure prevalence. However, these products may contain natural food preservatives like organic acids, antimicrobial agents that may not pose any serious affects to consumer's (Mariutti et al. 2011).

Due to the technological awareness, consumers are becoming more sophisticated about consuming safe and nutritious meat products. Meat and meat products are prone to microbial spoilage during slaughtering, processing and storage because they possess an ideal nutrient matrix that can favor the proliferation of micro-organisms especially pathogenic ones. Mostly, water activity of fresh meat fall in the range of 0.85–0.98 and they also provide an optimum pH for the growth of microorganism, so the chances of microbial contamination are evident (Dave and Ghaly 2011). Keeping in view of these conditions, it is essential to decontamination meat and allied products by using certain chemicals or intervention technologies to protect meat and meat based products from microbial degradation (Fratianni et al. 2010).

Microbes are mainly responsible for deterioration of safety and quality of meat products. These offensive changes in meat

lead to morbidity and are one of the major causes of food borne diseases. These pathogenic microorganisms possess greater socioeconomic impact due to their potential to contaminate meat and meat based products (Buzby et al. 2010). Major human pathogens of concern regarding microbial safety include *E. coli* O157:H7, *Salmonella* spp., *Campylobacter* spp., *Listeria monocytogenes*, *Clostridium botulinum/perfringens*, *Staphylococcus aureus* and *Bacillus cereu*. Besides, several other food spoilage microorganisms include *Pseudomonas*, *Acinetobacter/Moraxella*, *Aeromonas*, *Alteromonas putrefaciens*, *Lactobacillus*, and *Brochothrix thermospecta* (Borch and Arinder 2002). Among the pathogenic microorganisms, the incidence of *Salmonella* is ready to cooked meat is more common. There are various means to retard or control the incidence of spoilage caused by these pathogenic microorganisms in meat based systems s but all these processes involve artificial ingredients that can have deleterious effect on consumer's health.

The safety of meat based products can be increased by gathering authentic information of ingredients used in product development, the foremost challenge meat industry is facing currently. Lot of products are available in the market containing a variety of ingredients, so their safety may be a matter of concern for the consumers (Jean-Louis and Sylvie 2008). Food safety is the topmost priority for food and health authorities and consumers worldwide. Meat being a largely consumed food commodity that possesses an ideal medium for microbial growth has been brought to forefront. Food safety objectives (FSO) and hazard analysis and critical control point (HACCP) systems are being introduced and implemented worldwide to ensure the safety of meat based products. The European Union (EU) is now forcing authorities to implement extensive hygienic legislation as well as the established microbiological criteria (Jiang and Xiong 2014) into effect to control the incidence of food borne illnesses. Despite prodigious research efforts and investments, only few alternative preservation methods have been developed and implemented by the food industries worldwide. The main objective of this article is therefore to critically overview the possibilities of using different intervention technologies with special reference to development and production of safe meat and allied products.

Spoilage organisms of meat

The most prevailing spoilage organisms in meat are bacteria, yeast and molds. Due to the ubiquity of microorganisms, they are mostly incorporated in meat from environment. These organisms can cause spoilage by producing off odors in meat products. Bacterial spoilage of meat is more prominent as compared to others like yeast and molds.

Bacterial meat spoilage

Pathogenic bacteria are most important group of microorganisms that are responsible for deterioration of meat quality. These are mainly found in large intestine of animals and may infect the flesh after slaughtering if it is not properly dressed or handled. Bacterial contamination can be introduced through improper dressing practices, poor employee hygiene and contaminated knives or working areas that can leads to deterioration of product quality and safety (Nychas et al. 2008). The most commonly reported genera of bacteria on meat surface include *Sheela* spp., *E. coli*, *B. protest*, *Salmonella* spp., *S. epidermidis*, *S. aureus* and *B. cereus* (Lawrie and Ledward 2006). Psychotropic spore formers like *Clostridium* spp. can deteriorate meat quality by producing off odors even in brined and chilled meat products. The *Pseudomonas* spp. can spoil raw meat when stored under aerobic conditions. Lactic acid bacteria are also among the main contributor of meat products through production of off odor, slime generation through fermentation. Formation of butanol, butyric acid and sulfides through fermentation of glucose leads to the production of gases and off odors which cause meat spoilage called "Blown packed". The growth of lactic acid bacteria depends upon several factors like pH, water activity of the meat, oxygen and CO₂ level, as well as cooking and storage temperature towards which product was exposed (Doyle and Kathleen 2010).

Yeast as a meat spoilage agent

Yeasts possess slow growth rate compared to bacteria and are generally unable to compete with bacteria for nutrients in chilled/refrigerated environments. Although yeasts are present on carcasses, their populations make up less than 5 % of the total microflora. Yeast species that can significantly affect meat spoilage include *Candida mesenterica*, *Candida saitoana*, *Cryptococcus albidus*, *Cryptococcus laurentii*, *Cryptococcus luteolus*, *Rhodotrula glutinous*, and *Rhodotorula mucilaginosa* (Loeffler et al. 2014). Spoilage due to yeast contamination occurs when their population numbers reach 1×10^6 organisms/cm², a mass equal to bacterial counts of 1×10^8 organisms/cm² (Hinton et al. 2002).

Molds and spoilage of meat

Like yeasts, molds are also present in small proportion on surface of meat products. The most common fungal species of meat spoilage interest include *Acremonium*, *Alternaria*, *Aspergillus*, *Cladosporium*, *Epicoccum*, and *Penicillium* (Hinton et al. 2007). Environments that can promote mold growth include temperature range from -10 to -2 °C, water activity of 0.80, and pH range <1.0 to 11.0. Black mold, which is characterized by distinctive black spots on product surface is

most commonly caused by *Cladosporium cladosporioides*, *Cladosporium herbarum*, and *Penicillium hirsutum* (Jay 2000).

Postharvest intervention technologies

Intervention technologies for carcass decontamination

Post-harvest intervention techniques include carcass decontamination, antimicrobial additives and irradiation of carcass. Decontamination of beef and poultry carcass involve the use of chemical or physical approaches or the combinations of both. There are several factors to consider for the decontamination of meat (Table 1).

The methods for decontaminating poultry and red meat carcass are quite different. In poultry, antimicrobial are either added in chill water tank or sprayed after carcass chilling (Chen et al. 2014). Chlorine (hypochlorite, ClO₂) water is the most common and widely used antimicrobial in poultry processing plants in U.S., but not allowed to use in European Union (E.U). The incorporation of 18–25 ppm of chlorine into chill water can reduce salmonella significantly. The efficacy of chlorine increases linearly with concentration but higher concentration may results in discoloration, off-odor and also generate off-flavor in carcasses. Organic acids spray such as lactic acid and acetic acid at 1–2 % are also effective in reducing bacterial load in poultry but higher concentration of these acids tends to bleach the carcasses. Spraying or adding in chill water containing chemicals such as trisodium phosphate at 8–12 % (Capita et al. 2002), cetylpyridinium chloride at 0.5 %, ozonated water @ 0.03 ppm for chill water (Fabrizio et al. 2002), hydrogen peroxide (5 % for spray and 0.5–1.5 % for chill water), bacteriocins and activated lactoferrin are also permitted for decontamination of poultry carcass (Loretz et al. 2010). Reducing carcass temperature to <4 °C in chill water

Table 1 Factors to consider for application of decontaminants

Chemical composition of carcass of different animals
Safety aspects of different chemical s used: especially with reference to GRAS status of antimicrobial compounds?
Residues contaminated in the processed meat product
Impact of added chemical on sensory attributes of products
Nutritional value of processed meat products
Risk assessment for toxic compounds formation for different meat products
Water retention properties of carcass
Impact on spoilage and shelf life of meat products
Health and safety status of workers engaged in processing area in site microbial investigations to prove efficacy of different chemicals
Application method and concentration to be used
Will it be used as as “food additive” or “processing aid”?

quickly after slaughter is the primary means of preventing proliferation of pathogens in poultry (Table 2).

Decontamination techniques for red meat carcasses include live animal washing before slaughter, de-hairing through chemicals, removing physical contaminants using knife through trimming, spot cleaning through hot water, spray rinsing of carcass with water or with chemical solutions and pressurized steam, but steam vacuuming or washing carcass with water containing chlorine and organic acids solutions through spray washing tools (Omer et al. 2015). Steam vacuuming has been approved by the USDA in 1996 for use in commercial slaughter houses of beef. Theses process mainly uses hand-held equipment that can apply steam or water to loosen soil on surface of animal skin to kill the bacteria. Vacuum can also be applied in combination with water/steam to remove the contaminants or spots which are less than 2.5 cm in diameter. The process uses a vacuum of –0.0093 bar while a water nozzle inside the vacuum head spray hot water (>82 °C) or steam at 0.34–1.03 bar. Steam vacuuming is extensively used in U.S. by animal slaughtering industry as substitution for knife-trimming because it is relatively cheap and effective in removing visible accidental contamination. Carcass spray-washing uses either water, nonacid or organic acid solution. Nonacid solution that are permitted include chlorine (50 ppm), chlorine dioxide (20 ppm, 520 kPa 10 s), STP solution @8–12 % in beef, cetylpyridinium chloride (0.5 %) are used as spray wash solution.

Organic acid solution mainly acetic acid, lactic acid, or citric acid at 1.5–2.5 % are also adopted for decontamination of beef carcasses. The efficacy of decontamination is

Table 2 Meat spoilage agents and their effect generated on meat and meat products surface

Type of microbial agent	Oxygen requirement	Symptoms
Aerobic bacteria	Present	<ul style="list-style-type: none"> • Formation of surface slime • Discoloration of products • Production of gas • Change in odor • Fat decomposition take place
Anaerobic bacteria	Absent	<ul style="list-style-type: none"> • Putrefaction and foul odors • Gas production • Results in souring of meat products
Yeasts	Present	<ul style="list-style-type: none"> • Surface slime formation • Discoloration occurs • Change in odor and taste • Decomposition of fat in meat
Molds	Present	<ul style="list-style-type: none"> • Sticky and “whiskery” surface • Discoloration appeared • Change in odor • Results in fat decomposition

Adopted from (Lawrie and Ledward 2006)

determined mainly by water pressure, temperature of water, concentration of chemicals present and exposure time of carcass. Carcass spray-washing can accomplish 1–2 log reduction depending on the conditions (Park et al. 2005). Using hot water for decontamination of carcass includes immersion or cascading of hot water, rinsing with hot water at low pressure, spraying at high pressure or combinations of hot water, warm water, low pressure, and high pressure can result in 1–3 log reduction of bacteria. The application time ranges from 10 to 20 s and low pressure spray uses 20 psi and high pressure spray uses 125 psi for decontamination of carcass.

Chemical intervention technologies

Considering dietary health guidelines, there is a mounting demand for safe and healthy meat and meat based products that are linked with enhanced consumer knowledge during last decade. Meat spoilage can occur as a result of metabolic activity of microorganisms which are introduced on meat surface right after slaughtering. The presence of microbial flora on meat surface depends upon various factors including meat characteristics (residual glucose, pH), environmental conditions (temperature, atmosphere), type of packaging, initial microbial load and bacterial ability to grow (Mani-Lopez et al. 2012). Considering the microbes, the incidence of *Salmonella spp.* and *Campylobacter spp.* is a constant challenge for meat industry that can reduce the safety of fresh meat and meat based products (Whyte et al. 2001). Several recent studies concluded that if moist atmosphere is provided to meat surfaces, a group of bacteria may cause spoilage particularly when meat and allied products are stored at –10 to 5 °C (Loretz et al. 2010). Keeping in view the detailed discussion about use of different chemical intervention technologies is as under;

Organic acids as antimicrobial agent

Application of organic acids like propionic acid, lactic acid, citric acid, acetic acid and benzoic acid for decontaminating

meat surfaces is widely used mainly due to their availability, cost effective approach, simple to use and efficiency without imparting any health problems (Mataragas et al. 2008). Growth inhibitors including salts of organic acids are applied in meat based products owing to their potential to retard microbial growth. Besides this, food grade salts, including sodium lactate, potassium lactate, sodium citrate, and sodium diacetate not only exhibit antibacterial activity but also function as pH controllers, humectants and flavor in allied meat products (Gottlieb et al. 2006). Furthermore, organic acids are considered generally recognized as safe (GRAS) for application in meat and meat products by FDA. The Table 3 comprehensively depicts their applications in meat, mode of action and targeted microorganism. Several studies are conducted to verify the decontamination potential of organic acids in food particularly using meat based models. The results concluded that organic acid application may induce some sensorial changes (color and flavor) in meat products. The mechanistic approach of these acids involve that they enter the microbial body, induce cytoplasmic acidification that can lead to imbalance of energy. The second approach elaborate that their application results in accumulation of free acid anions to a toxic level that can kill or at least retard the growth of these microbes (Gonzalez-Fandos et al. 2009). One of the researchers groups, Morey et al. (2014) explicated the mechanism of microbial inactivation of organic acids and they proposed that these acids accumulate in the microbial cytoplasm. This acid accumulation decreased the pH rapidly which disturbed the optimal enzymatic activity and adversely affects the protein and DNA/RNA synthesis. Likewise, Drosinos et al. (2006) also reported that accumulation of acid anion can decrease proton motive force (PMF) that can result in microbial cytoplasm fails to re-alkalinize. Organic acid solutions (1–3 %) containing lactic and acetic acid are now widely used in commercial beef and lamb dressing plants for decontamination against microorganisms. Other organic acids such as ascorbic, fumaric, citric, propionic and formic acid are also deployed for carcass rinsing. These solutions are effective when used as warm solutions 50–55 °C (Theron and Lues 2007).

Table 3 Organic acids as antimicrobial agents in meat products

Compounds	Microbial target	Action mechanism	Primary food applications
Acetic acid, acetates, diacetates, dehydroacetic acid	Yeasts, bacteria	Cytoplasmic acidification results in malfunction of energy production and regulation parameters which results in accumulation of free acid anion to a toxic limit that can kill or retard the growth of the microbes	Dairy products, meats
Lactic acid, lactates	Bacteria	Establishment of a transmembrane gradient by the diffusion of an dissociated acid through a microbial membrane	Meats, fermented foods
Sodium propionate	Molds	Cytoplasmic acidification results in malfunction of energy production and regulation parameters which results in accumulation of free acid anion to a toxic limit that can kill or retard the growth of the microbes	Meat products

Source: Food and Drug Administration (FDA)

A study by Liao et al. (2003) reported that acetic acid applied different strains of *Salmonella* in range of 0.06 to 3.0 % using Heart Infusion Agar (BHIA) showed that their relative susceptibility of different strains was in the following order as; *S. bareilly*, *S. typhimurium*, *S. montevideo*, *S. poona*, *S. mbandaka* and *S. Stanley*. Similarly, Zhou et al. (2007) assessed the antibacterial potential of acetic acid (0.10 %) in combination with thyme (100 mg/L) and carvacrol (100 µl/L) and reported synergetic behavior of acetic acid with these compounds enough to inhibit *S. typhimurium* activity without affecting flavor of poultry meat. It is also concluded from that finding that moderately low temperatures (10 °C) can significantly decrease resistance of microorganisms against these acid. Moreover, lower pH facilitates to decrease ability of microorganisms to survive against lower temperature (Alvarez-Ordóñez et al. 2010). Milillo and Ricke (2010) conducted study to determine minimum inhibitory concentrations (MIC) of sodium citrate and sodium lactate in chicken meat for *S. typhimurium*. The results elucidated that recorded MIC were 1.25 and 2.5 % for sodium citrate and sodium lactate at 37 °C. Laury et al. (2009) conducted a study in which they sprayed a blend of citric and lactic acid on surface of broiler meat and noticed 1.3 logs CFU/mL reduction of *Salmonella* population while immersion of carcass in that solution for 20 s resulted a 2.3 logs CFU/mL of pathogenic microorganism and the description of decontamination potential of various organic acids against *Escherichia coli* 0157:H7 is elaborated in Table 4.

Lactic acid finds applications in food based models to improve color and flavor of the product. It can also prevent oxidative degradation in meat based products (Bosilevac et al. 2006) and can be used as antimicrobial agent for surface decontamination of carcasses (USDA-FSIS 2010). A study conducted by Harris et al. (2006) in which they sprayed 2.0–4.0 % lactic acid solution on beef surfaces and delineated that *E. coli* O157:H7 and *Salmonella* population were significantly decreased up to 1.5 to 2.0 logs. Likewise, Over et al. (2009) also found a significant reduction in bacterial populations of treated chicken breast samples at a concentration of 150 mM during storage at 4 °C. Several other studies stated that

spraying 1.0 to 1.25 % lactic acid on veal carcasses significantly decreased bacterial count during storage at 4 °C for 14 days. Moreover, higher concentrations greater than 2 % led to surface discoloration of meat products. Propionic acid and its salt are recognized as GRAS for usage in meat products and mechanistic approach of propionic acid is exactly similar to other acids but its action time as less compared to other acids. The mechanism of propionic acid involved to hinder cell division by blocking synthesis of DNA and proteins of cell.

Tartaric and malic acid are dicarboxylic acids, abundantly found in fruits and berries. Both acids are included in GRAS category by FDA and are considered safe for food application. These acids are generally weak antimicrobial agents and are less effective for surface decontamination. A study reported by Tamblyn and Conner (1997) in which they treated chicken breast meat with 0.5 and 1 % malic acid stored at 4 °C for 60 min and recorded 1.2 to 2.16 log reduction of *S. typhimurium*, respectively. They further applied malic acid under scalded conditions at 50 °C for 2 min and found 1.62 logs reduction of microorganism. Another study by Over et al. (2009) in which they applied 150 mM of tartaric and malic acid combination under vacuum conditions to estimate growth of *Salmonella* using boneless breast meat. They did not report any count even after 9 days of refrigeration storage.

Tri-sodium phosphate (TSP) is used for decontamination of meat and also for removal of microbes on the surface of meat. Higher concentrations of TSP (8–12 %) can be used to decontaminate raw meat significantly. Mostly TSP is applied on surface of beef by spraying method that can increasing pH to level undesired for growth of pathogenic bacteria. A study by Whyte et al. (2001) reported that TSP (1 %) can be used in combination with Tween-80 (5 %) to reduce the total count of *Salmonella*, *L. monocytogenes*, *E. coli* and total plate count (TPC) by 1 to 3 log 1 CFU/cm² in meat tissues. Moreover, Pohlman et al. (2002) concluded that TSP (10 %) apparently reduced microbial populations in beef samples that also improved color of meat product. These studies suggest the potential of aforementioned organic acids for decontamination of meat based products against pathogenic bacteria.

Table 4 Decontamination of meat containing inoculated *Escherichia coli* 0157:H7

Tissue	Method	Decontamination potential	Reference
Lean beef	2 % lactic acid	0.50 log reduction	(Laury et al. (2009))
	2 % lactic acid and alginate dip	0.74 log reduction	
Lean beef and adipose tissues	1, 3, 5 % lactic, acetic, citric	1 to 2 log reduction	(Harris et al. 2006)
	Pilot scale washer		
Lean beef	1.5 % lactic, citric acid spray At 20–55 °C	0.3 to 0.5 log reduction	(Rojas et al. 2007)
Lean beef	1 % lactic acid	0.78 log reduction	(Cutter and Siragusa 1996)
	1 % acetic acid	0.63 log reduction	
	1.5 % fumaric dip	1.96 log reduction	

Chlorine

Chlorine is among widely accepted and feasible intervention technology used for decontamination of animal origin products particularly in poultry and beef industry. Major benefits of using chlorine are that it is cheap, easy to apply in carcass and especially its efficiency against microbes including Gram-positive and negative bacteria. The action mechanism of chlorine involves its strong oxidative potential that can disrupt bacterial cell wall leading to enzymes inactivation which can cleavage bacterial DNA (Yang et al. 2009). Chlorine solutions are also known to lower total bacterial counts even at low concentrations like (200 ppm) can decrease total bacterial counts in beef carcass (Sheen et al. 2011). Several studies reported the decontamination potential of chlorine. One of the researchers groups, Sofos (2008) reported that *Escherichia coli* O157:H7 and *Salmonella* in beef and poultry meat can be removed or reduced using chlorine at various concentrations. One of the limitations of using chlorine for carcass decontamination is, it can be easily neutralized by organic matter so using chlorine before de-hiding of animal is not a wise and practical approach. It is always advised that chlorine should be applied after de-hiding. Otherwise, large amount of chlorine will be neutralized by organic matter adhered with hides. Despite its numerous benefits, using chlorine in food based products is toxic so its concentration must be controlled efficiently. The reaction of chlorine with organic material can generate carcinogenic compounds like trihalomethanes that can pose a serious threat for workers in meat industries (Richardson 2003). The guidelines have been set by Australia and the EU members countries for safe application of chlorine in food particularly meat industries that do not allow chlorine above 10 ppm for food industries. However, United States regulations permit higher concentration of 20 ppm for poultry washes/sprays and for poultry chill tanks 50 ppm is permitted (Byelashov and Sofos 2009).

Carbon dioxide

Carbon dioxide (CO₂) is a part of modified atmosphere packaging (MAP) systems used to extend shelf life of stored foods but its effectiveness to inactivate microbial growth still needs more scientific confirmation. A study by Guan and Hoover (2005) reported that CO₂ in combination with technologies like pulsed electric field and high pressure has shown capacity to kill pathogenic bacteria including *E. coli*, *Salmonella* and *Listeria* in packaged meat products based on these evidences, CO₂ can be applied in meat industry for controlling the growth of microorganisms.

Peroxyacetic acid

Peroxyacetic acid is applied as a carcass washing agent in beef processing plants. Generally, 0.02 % solution of peroxyacetic

acid is used to decrease microbial load on red meat. In a study by Ransom et al. (2003) stated that application of peroxyacetic acid solution (0.02 %) resulted in 1–1.4 log reduction of *E. coli* O157:H7 in beef tissues. In another trial, reduction in total population of bacteria and *E. coli* was noticed when same concentration was applied on chilled beef carcasses (Gill and Holley 2003). Similarly, King et al. (2005) indicated that higher dose of peroxyacetic acid is able to decrease *E. coli* O157:H7 and *Salmonella typhimurium* effectively (<0.2 log) but showed better results when applied on hot carcasses. The Food Safety and Inspection Service (FSIS) in USA allowed the use of peroxyacetic acid for decontamination of beef carcass.

Acidic calcium sulfate

Acidified calcium sulfate (ACS) also known to have bacteriostatic effects. It is particularly used to decrease pathogens in processed meat products. A study by Zhao et al. (2004) proposed that ACS in combination with lactic acid yielded good results to inactivate bacteria in ground beef and hot dogs. The use of ACS is also effective against *Listeria monocytogenes* in processed meat products. The inhibition of foodborne pathogens can be enhanced by using antimicrobials in combination. In this regard, Brandt et al. (2011) conducted a study to estimate the effects of octanoic acid (OCT) and acidic calcium sulfate (ACS) on inhibition of *Listeria monocytogenes*. The results indicated that this combination enhanced the inhibition of pathogen. MICs for OCT and ACS were 25.00 µg/g and 1.56 ml/l, respectively, for all strains of the pathogen tested.

Activated lactoferrin

Lactoferrin is an antimicrobial agent and its main sources are milk, saliva, tears, and in trace present in meat tissue. Activated lactoferrin (ALF) can be applied on meat surface during processing or on finished product just before packaging. It is used for poultry meat decontamination at a level of 2 %. The mechanistic approach of ALF involves that it can rupture cell membrane of bacteria and binds iron in cell. It is also effective against variety of pathogens including *Listeria monocytogenes*, *E. coli* and *Salmonella* (Taylor et al. 2004). A study reported by Ransom et al. (2003) reported that meat treated with lactoferrin was vacuum packed and stored at freezing condition for 35 days. The results revealed that activated lactoferrin significantly inhibited the growth of *E. coli*, *Salmonella typhimurium* and *Listeria monocytogenes* in vacuum-packaged beef.

Cetylpyridium chloride

Cetylpyridium chloride (CPC) is considered a strong antimicrobial agent and its action mechanism involve the formation

of ionic interaction between cetylpyridinium ions with acidic molecules that can interrupt bacterial respiration. Several studies report that washing poultry carcasses with 0.5 % CPC can reduce up to 2.5 log of *Salmonella Typhimurium* (Kim and Slavic 1996). In a study by Cutter et al. (2000), they sprayed 1 % CPC solution on beef carcass and recorded *E. coli* O157:H7 and *Salmonella Typhimurium* reduction up to 5–6 log CFU/cm². Similarly, Pohlman et al. (2002) applied 0.5 % CPC solution on beef before mincing and reported 1 log reduction of microbes without disturbing sensorial attributes of minced beef. Likewise, CPC is also effective (5 log reduction) during refrigerated storage of beef carcasses after spray-chilling with CPC (Stopforth et al. 2004).

Ozone

Ozone is naturally occurring water-soluble gas that can act as strong oxidizing. It can attack on cellular membrane of bacterial cells after exposure with ozone. Ozone is a very effective germicide against viruses, bacteria, spores and stored grain insects (Bonjour et al. 2008). A study conducted by Bosilevac et al. (2005) found that application of ozonized water in a simulated hide washing system can result significant reduction of aerobic plate count up to 2.1 log compared with plain water (0.5 log reductions). Similarly, ozone has the capacity to decontaminate the red meat surfaces against microbial spoilage. Generally, there are no restrictions to use ozone for food applications because of no residual effects and it is regarded safe (FDA 2003).

Biological intervention technologies

Nowadays, consumers worldwide demand high quality and safe food products contain natural ingredients. In response to this changing demand, the meat industry has been looking for practical ways to ensure safety and quality meat products. Biological intervention technologies to control microbial spoilage of meat and meat products mostly involve bacteriophages and bacteriocins which have shown a good potential to decontaminate microbes and are now widely used in meat and food industries. Food safety status of meat products can also be improved by deploying natural ingredients like several plant extracts and their essential oils to hinder the growth of microflora, like lactic acid bacteria and their metabolic products, bacteriocins etc. (Hugas et al. 2002). Recently, several research scientists are focusing to explore natural ingredients like antimicrobial agents for food and meat preservation (Tiwari et al. 2009). Even though, the results claims of biological interventions are widespread but they are widely used by industry mainly due to increase demand for natural and chemical free foods. So this section will briefly review the most widely used biological intervention technologies in meat and meat products.

Essential oils and plant extracts

Use of natural compounds for enhancing meat quality has been increased rapidly due to health concerns of consuming chemically treated meat products. Using natural antimicrobial agents for preservation and enhancing microbial safety of meat based products is major step in this regard (Tiwari et al. 2009). Plant extracts and essential oils contain variety of compounds that possess capacity to retard growth of microorganisms (Chorianopoulos et al. 2008). Some commonly used plant extracts include garlic, ginger, pimento, clove and rosemary as well as essential oils extracted from plants such as *Picea excels*, *Camellia japonica* and *Thymus eigii*. These natural extracts are claimed to possess good preservative capacity when coupled with other technologies to mitigate microbial load in meat (Zhu et al. 2005). Usually, essential oils are more effective against Gram-positive bacteria compared to Gram-negative bacteria (Gutierrez et al. 2008). Several studies confirm the antimicrobial potential of these natural extracts (Bajpai et al. 2008).

Accordingly, Karabagias et al. (2011) noticed a significant reduction (2.8 logs) in microbial population in lamb meat by deploying a combination of modified atmosphere packaging and 0.1 % essential oil extracted from thyme. Another study reported 1.12 log reduction of *E. coli* O157:H7 populations in beef meat when coated with 1 % oregano essential oil (Oussalah et al. 2004). Likewise, Mastromatteo et al. (2009) also concluded that chicken meat quality can be enhanced by treating it with thyme and carvacrol at concentration of 300 ppm/kg meat. Moreover, green tea and grape seed extracts also possess capacity to preserve meat quality by hindering microbial spoilage (Perumalla and Hettiarachchy 2011). Similarly, Xi et al. (2012) explored the effects of natural antimicrobial agents in controlling *Listeria monocytogenes* in frankfurters in the population. These studies suggest that natural antimicrobial agents and plant extract are effective to control microbial degradation in allied meat products. However, there is need to conduct more studies to explicate the effect these extracts on pathogenic compounds on microbial status of meat to find optimum treatment conditions that can offer good sensory attributes.

Bacteriophages and parasitic bacteria

Bacteriophages are viruses of microbial group that can attack host microorganisms and possess a potential to destroy them. In this regard, Greer (2005) purified virulent strains of bacteriophages, fed to the cattle and found a significant reduction of *E. coli* O157:H7 in them. Bacteriophages are natural products and do not have detrimental environmental effects. Moreover, due to their high host specificity they do not cause harm to probiotics in gastrointestinal tract. Due to this specificity care should be taken in the selection of the certain strains against a specific host. Furthermore, excessive use of a particular strain for inhibition of a specific group of bacteria can develop

resistance in target microorganisms through their natural evolutionary process (Loretz et al. 2010). Additionally, several parasitic bacteria, especially *Bdellovibrio bacterivorus* are also used to prevent food spoilage (Hanlin and Evancho 1991). These organisms are frequently found in soil and fecal residues of many species, and can be easily isolated and purified. There are evidences of their food applications from literature. *Bdellovibrio* reduced *E. coli* and *Salmonella* to 2.5 to 7.9 log during 7 h in culture and 3.0–3.6 log in stainless steel in 24 h. These organism shows optimum activity at 30–37 °C but its parasitic activity was reported between 12 to 19 °C. Similarly, Hudson et al. (2014) indicated that UV-treated phages in milk inactivated *E. coli* O157:H7 on surface of raw and cooked meat. The results elucidated that minimum concentration 10^5 PFU cm^{-2} of UV-treated phages was required for inactivation of *E. coli* O157:H7 on meat surface and a reduction of 1–2 \log_{10} CFU cm^{-2} was observed at concentration of 10^7 UV-treated phages cm^{-2} .

Bacteriocins

Bacteriocins are unique antimicrobial peptides that are produced by different bacterial strains (Galvez et al. 2007). They can be added to raw or cooked meat during their processing or before packaging to inhibit growth of spoilage microbes. Nisin and pediocin are claimed to have antimicrobial effect in meat and meat products. Surface application of niacin followed by vacuum packaging of meat can enhance antimicrobial activity of meat. Moreover, niacin give good results in decontaminating meat surface when applied in combination with alginate-based edible coatings. Accordingly in a study, Ming et al. (1997) reported that sausages can be preserved by treating their inner surface with bacteriocins. They also applied niacin and pediocin to inner side of packaging materials and noticed a significant reduction for *Listeria monocytogenes* in breast turkey meat, ham and beef under refrigerated storage. However, efficacy of bacteriocins is reported lower in food systems compared to culture media under laboratory conditions due to binding of bacteriocins with food matrix that can inactivate enzymes, precipitation of particles and uneven distribution of bacteriocin with in food matrix.

Multiple hurdle approach to control microbial spoilage

The sequential use of effective microbial decontamination technologies is termed as ‘multiple hurdle’. Hide removal and rapid carcass chilling in combination with a number of physical and chemical decontamination techniques reduce microbial load on the carcass, which is further helpful to inhibit microorganisms in subsequent processing steps (Chouliara et al. 2007). Several studies also claimed that the reduction of pathogens in livestock prior to slaughter was helpful in reducing carcass contamination after slaughtering. To control

pathogenic bacteria during processing, handling and subsequent storage, various strategies such as addition of antimicrobial agents, heat treatment, temperature control and post-packaging intervention (e.g., irradiation) are used commonly. Although these intervention technologies are effective but using increased levels of certain preservatives or high dose of irradiation in meat products may negatively alter the sensory characteristics of the meat products. These problems can be circumvented by employing hurdle technology involving the use of a combination of preservation techniques. In addition physical antimicrobial treatments such as heating or irradiation can also be applied to the packaged products to enhance the antimicrobial effect of the added preservatives (Zhou et al. 2010). The multiple hurdle, however, should include pre-harvest, post-harvest and post-processing intervention technologies at appropriate levels to ensure the safety level of meat and meat products.

Other innovative processing approaches

There are several other processing technologies that are approved for bacterial reduction in meat products but their use is still limited. These processes include ionizing irradiation, hydrostatic pressure, electric fields, pulsed light, intelligent packaging, sonication and microwaves (Sofos and Busta 2001).

Intelligent packaging

Packaging plays an important role in preventing microbial spoilage by controlling physical, chemical, and sensorial changes in food systems (Graham 2001). Intelligent packaging involves the addition of different antimicrobial compounds like organic acids etc. in packaging material. These compounds interact with packaging material and protect food present in it (Zhou et al. 2010). Cooked, cured red meat and fish can be preserved using vacuum-packaging technique. Vacuum-packaging also maintains red color and soft texture of meat during storage (Jeong and Claus 2011). Modified atmosphere packaging (MAP) can also be used to preserve meat based products. Several factors such as type of meat, storage facilities and storage condition determine whether food should be stored in vacuum-package bags or oxygen permeable bags (Adams and Moss 2000).

High pressure processing

High pressure processing (HPP) is a novel non thermal technique that can be used to retard the growth of different pathogens to ensure the safety of meat and meat products (Jofre et al. 2009). This technology involves application of high pressure to packaged food to avoid contamination during processing. Generally, 400 to 600 MPa pressure is applied to inhibit activity of most vegetative pathogenic microorganisms

at room temperature. Similarly, major food borne pathogens (*E. coli* O157:H7, *Salmonella* and *L. monocytogenes*) can be controlled by applying pressure between 400 to 600 MPa (Black et al. 2010). Similarly in a study by Clariana et al. (2011) indicated that using higher pressure up to 600 MPa for 6 min at 15 °C retard the microbial growth by maintaining color characteristics of dry-cured ham.

Ultrasound technology

Ultrasound technology involves the use of high pressure, shears forces and temperature gradient to generate ultrasound waves of 20 to 100 kHz that can damage cell membranes and disrupt the DNA of microorganisms (Morild et al. 2011). Ultrasound technology is suitable for poultry carcasses decontamination because it involves the immersion of product in ultrasound bath for treatment. Ultrasonic waves are safe and non-toxic, therefore gained acceptance for use in meat products as an antimicrobial agent. The effect of ultrasound on different microorganisms is known to depend on shape, size and type of cells as well as physiological state of microorganisms (Rastogi 2010). Accordingly, Kordowska-Wiater and Stasiak (2011) used ultrasound waves alone and in combination with lactic acid and reported a significant reduction of 1 log CFU/cm² and 1.5 log CFU/cm² respectively for gram negative bacteria in poultry meat.

Irradiation

Irradiation is very effective technology to control foodborne pathogens and can be applied in meat based products to increase safety and shelf-life by improving quality and maintaining nutrient content during storage (Kume et al. 2009). Irradiation is also very effective technique to control the microbial growth and to enhance the microbial safety of meat (Cambero et al. 2012). Irradiation involves preservation of food without using chemicals. Moreover, products are treated after final packaging that reduces the chances of cross contamination during post-processing handling. In 1999, the USDA-FSIS approved the use of x-rays, gamma rays and electron beams to reduce pathogenic bacteria of raw and processed meat (FSIS 2010). A dose of up to 4.5 kGy is approved for use on refrigerated meat products whereas a dose of up to 7.0 kGy is approved for frozen meat products. The populations of most common enteric pathogens such as *Campylobacter jejuni*, *E. coli* O157:H7, *Staphylococcus aureus*, *Salmonella* spp., *L. monocytogenes*, and *Aeromonas hydrophila* can be significantly decreased or eliminated by low-dose (<3.0 kGy) irradiation (Ahn et al. 2013). Irradiation has been found to be effective to reduce bacterial population up to 6.0 log CFU/cm² in meat products (Arthur et al. 2005). However, high dose of radiations can cause detrimental effects on meat quality by producing off-flavor such as rotten egg, fishy, barbecued, burnt,

and acetic acid (Brewer 2009). The bacteriocidal action of ionizing irradiation is linked to bacterial DNA damage free radicals produced during the irradiation process and the extent of damages is dose-dependent (Oreai et al. 2011). There are several studies that suggest that irradiation can be applied in combination with other chemicals and technologies that yield better decontamination of meat. In this regard, Jin et al. (2009) reported that combination of pectin-nisin films with ionizing radiation increased microcidal effects of irradiation. Combinations of organic acid and irradiation were more effective than each intervention alone for retarding total microbial counts and coliforms in pork during storage (Kim et al. 2004). Generally, combination of irradiation and organic acid did not alter the sensorial attributes negatively in frankfurters (Chen et al. 2004).

Pulsed electric field

Pulsed electric field (PEF) involves the use of a short blast of high electrical voltage to different food products kept at room or refrigeration temperature (Zhou et al. 2010). By applying, PEF the cell membrane of microorganisms is damaged due to higher voltage which leads towards death of microorganism (Haughton et al. 2011). During PEF application, heat is generated due to higher voltage but it does not impart any deteriorative effect on meat quality due to shorter application time span. Several studies reported contradictory findings regarding the use of PEF in meat and meat products (Keklik et al. 2010). In this context, Bolton et al. (2002) stated that use of pulse electric field was not effective in controlling *E. coli* O157:H7 growth in beef. The reason behind that incapability may be due to low voltage and high protein and fat contents of beef. Another study reported that a dose of 7 kV/cm was effective in hindering the growth of *E. coli* in meat (Rojas et al. 2007). Paskeviciute et al. (2011) used high power pulsed light for decontamination of chicken meat surface and reported its antimicrobial efficacy without affecting organoleptic attributes. Hierro et al. (2011) also found pulsed light effective against *Listeria monocytogenes* in ready-to-cook meat products. These finding proved the decontamination potential of pulsed electric field for the decontamination of meat based products. However, further studies may be required to verify the potential of PEF before accepting its widespread application in meat industry.

Conclusions

Regardless of availability of sophisticated technologies and programmed efforts to minimize the incidence of microbes in meat industry, still, it is among concerns of high attention for meat professionals and consumers. Reducing or eliminating pathogenic microorganisms that are human pathogens as well as can cause meat spoilage is prime goal of meat industry.

The potential sources of microbial contamination include fecal material, paunch and hide, processing tools & equipment, structural facility, human contact, carcass-to-carcass contamination and environment. Generally used post-harvest interventions are use of chemicals, biological and their combination. However, these studies suggest that animal species and meat type can affect the incidence of microorganism. There is no singlet procedure or technology that can ensure microbial safety of meat based products. However, sequential use of effective decontamination technologies termed as ‘multiple hurdle is quite effective and also innovative approaches may be applied for enhancing the safety of meat products. During selection of intervention technologies for meat decontamination, not only effectiveness of method should be considered but also its effect on quality and sensory attributes should be taken into account carefully.

References

- Adams MR, Moss MO (2000) The microbiology of food preservation. In: Food Microbiology, 2nd ed. Royal Society of Chemistry
- Ahn DU, Kim S, Lee EJ (2013) Irradiation and additive combinations on the pathogen reduction and quality of poultry meat. *Poult Sci* 92: 534–545
- Alvarez-Ordóñez A, Fernández A, Bernardo A, López M (2010) Acid tolerance in *Salmonella typhimurium* induced by culturing in the presence of organic acids at different growth temperatures. *Food Microbiol* 27:44–49
- Arthur T, Wheeler T, Shackelford S, Bosilevac J, Nou X, Koohmaraie M (2005) Effects of low-dose, low-penetration electron beam irradiation of chilled beef carcass surface cuts on *Escherichia coli* O157:H7 and meat quality. *J Food Prot* 68:666–672
- Aymerich T, Picouet PA, Monfort JM (2008) Decontamination technologies for meat products. *Meat Sci* 78:114–129
- Bajpai VK, Rahman A, Dung NT, Huh MK, Kang SC (2008) In vitro inhibition of food spoilage and foodborne pathogenic bacteria by essential oil and leaf extracts of *Magnolia liliflora* Desr. *J Food Sci* 73:314–320
- Black EP, Hirneisen KA, Hoover DG, Kniel KE (2010) Fate of *Escherichia coli* O157:H7 in ground beef following high-pressure processing and freezing. *J Appl Microbiol* 108:1352–1360
- Bolton DJ, Catarame T, Byrne C, Sheridan JJ, McDowell DA, Blair IS (2002) The ineffectiveness of organic acids, freezing and pulsed electric fields to control *Escherichia coli* O157:H7 in beef burgers. *Lett Appl Microbiol* 34:139–143
- Bonjour EL, Jones CL, Noyes RT, Hardin JA, Beeby RL, Eltiste DA, Decker S (2008) Efficacy of ozone against insect pests in wheat stored in steel grain bins. In: Proceedings of the 8th International Conference on Controlled Atmosphere and Fumigation in Stored Products. pp. 522–529
- Borch E, Arinder P (2002) Bacteriological safety issues in red meat and ready-to-eat meat products, as well as control measures. *Meat Sci* 62:381–390
- Bosilevac JM, Shackelford SD, Brichta DM, Koohmaraie M (2005) Efficacy of ozonated and electrolyzed oxidative waters to decontaminate hides of cattle before slaughter. *J Food Prot* 68:1393–1398
- Bosilevac JM, Nou XW, Barkocy-Gallagher GA, Arthur TM, Koohmaraie M (2006) Treatments using hot water instead of lactic acid reduce levels of aerobic bacteria and Enterobacteriaceae and reduce the prevalence of *Escherichia coli* O157:H7 on pre-visceration beef carcasses. *J Food Prot* 69:1808–1813
- Brandt AL, Alejandro C, Harris KB, Keeton JT, Hardin MD, Matthew TT (2011) Synergistic Inhibition of *Listeria monocytogenes* In Vitro through the Combination of Octanoic Acid and Acidic Calcium Sulfate. *J Food Prot* 166:122–125
- Brewer M (2009) Irradiation effects on meat flavor: a review. *Meat Sci* 81:1–14
- Buzby JC, Frenzen PD, Rasco B (2010) Product liability and foodborne illness. Washington, DC: Food and Rural Economics Division, Economic Research Service, U.S. Department of Agriculture, 2001; Available at: <http://www.ers.usda.gov/Publications/AER799/> Accessed 20 Dec 2010
- Byelashov OA, Sofos JN (2009) Strategies for on-line decontamination of carcasses. In: Toldra F (ed) Safety of Meat and Processed Meat. Springer, New York
- Cambero MI, Cabeza MC, Escudero R, Manzano S, Garcia-Marquez I, Velasco R, Ordóñez JA (2012) Sanitation of selected ready-to-eat intermediate-moisture foods of animal origin by E-beam irradiation. *Foodborne Patho Dis* 9:594–599
- Capita R, Alonso-Calleja C, Garcia-Fernandez MC, Moreno B (2002) Review: trisodium phosphate (TSP) treatment for decontamination of poultry. *Food Sci Technol Int* 8(1):11–24
- Centers for Disease Control and Prevention (2010) Surveillance for foodborne disease outbreaks—United States, 2007. *MMWR* 59: 973–979
- Chen CM, Sebranek JG, Dickson JS, Mendonca AF (2004) Combining pediocin with postpackaging irradiation for control of *Listeria monocytogenes* on frankfurters. *J Food Prot* 67:1866–1875
- Chen X, Bauermeister LJ, Hill GN, Singh M, Bilgili SF, McKee SR (2014) Efficacy of various antimicrobials on reduction of salmonella and campylobacter and quality attributes of ground chicken obtained from poultry parts treated in a postchill decontamination tank. *J Food Prot* 77:1882–1888
- Chorianopoulos N, Kalpoutzakis E, Aligiannis N, Mitaku S, Nychas GJ, Haroutounian SA (2008) Essential oils of *Satureja*, *Origanum*, and *Thymus* species: chemical composition and antibacterial activities against foodborne pathogens. *J Agric Food Chem* 52:8261–8267
- Chouliara E, Karatapanis A, Savvaidis IN, Kontominas MG (2007) Combined effect of oregano essential oil and modified atmosphere packaging on shelf-life extension of fresh chicken breast meat, stored at 4 °C. *Food Microbiol* 24:607–617
- Clariana M, Guerrero L, Sarraga C, Diaz I, Valero A, Garcia-Regueiro JA (2011) Influence of high pressure application on the nutritional, sensory and microbiological characteristics of sliced skin vacuum packed dry-cured ham: effects along the storage period. *Innov Food Sci Emerg Technol* 12:456–465
- Cutter CN, Siragusa GR (1996) Reduction of *Brochothrix thermosphacta* on beef surfaces following immobilization of nisin in calcium alginate gels. *Lett Appl Microbiol* 23:9–12
- Cutter CN, Dorsa WJ, Handie A, Rodriguez-Morales S, Zhou X, Breen PJ, Compadre CM (2000) Antimicrobial activity of cetylpyridinium chloride washes against pathogenic bacteria on beef surfaces. *J Food Prot* 63:593–600
- Dave D, Ghaly AE (2011) Meat spoilage mechanisms and preservation techniques: a critical review. *Am J Agri Biol Sci* 6:486–510
- Doyle ME, Kathleen AG (2010) Sodium Reduction and Its Effect on Food Safety, Food Quality, and Human Health. *Com Rev Food Sci Food Saf* 9:44–56
- Drosinos EH, Mataragas M, Kampani A, Kritikos D, Metaxopoulos I (2006) Inhibitory effect of organic acid salts on spoilage flora in culture medium and cured cooked meat products under commercial manufacturing conditions. *Meat Sci* 73:75–81

- European Food Safety Authority (2011) The European Union summary report on trends and sources of zoonoses, zoonotic agents and food-borne outbreaks in 2009. *EFSA J* 9:2090
- Fabrizio KA, Sharma RR, Demirci A, Cutter CN (2002) Comparison of electrolyzed oxidizing water with various antimicrobial interventions to reduce *Salmonella* species on poultry. *Poult Sci* 81(10):1598–1605
- FDA (2003) Code of Federal Regulations. Title 21. Government Printing Office, USA
- Frazianni F, Martino LD, Melone A, Feo VD, Coppola R, Nazzaro F (2010) Preservation of chicken breast meat treated with thyme and balm essential oils. *J Food Sci* 75:528–535
- FSIS (2010) Safe and suitable ingredients used in the production of meat and poultry products. 21 Code of Federal Regulations (CFR). FSIS Directive 7120:1–41
- Galvez A, Abriouel H, Lopez RL, Ben ON (2007) Bacteriocin-based strategies for food biopreservation. *Int J Food Microbiol* 120:51–70
- Gill AO, Holley RA (2003) Interactive inhibition of meat spoilage and pathogenic bacteria by lysozyme, nisin and EDTA in the presence of nitrite and sodium chloride at 24 °C. *Int J Food Microbiol* 80:251–259
- Gonzalez-Fandos E, Herrera B, Maya N (2009) Efficacy of citric acid against *Listeria monocytogenes* attached to poultry skin during refrigerated storage. *Int J Food Sci Technol* 44:262–268
- Gottlieb SL, Newbern EC, Griffin PM (2006) Multistate outbreak of listeriosis linked to turkey deli meat and subsequent changes in US regulatory policy. *Clin Infect Dis* 42:29–36
- Graham BR (2001) Meat packaging. In: Young OA, Rogers RW, Hui YH, Nip WK (eds) *Meat Science and Applications*. CRC Press, Boca Raton
- Greer GG (2005) Bacteriophage control of foodborne bacteria. *J Food Prot* 68:1102–1111
- Guan D, Hoover DG (2005) Emerging decontamination techniques for meat. In: Sofos JN (ed) *Improving the Safety of Fresh Meat*. Woodhead Publishing Limited, CRC Press, New York
- Gutierrez J, Rodriguez G, Barry-Ryan C, Bourke P (2008) Efficacy of plant essential oils against foodborne pathogens and spoilage bacteria associated with ready-to-eat vegetables: antimicrobial and sensory screening. *J Food Prot* 71:1846–1854
- Hanlin JH, Evancho GM (1991) The beneficial role of microorganisms in the safety and stability of refrigerated foods. In: Dennis C, Stringer ME (eds) *Chilled Foods a Comprehensive Guide*. Horwood Ltd., Chichester
- Harris K, Miller MF, Loneragan GH, Brashears MM (2006) Validation of the use of organic acids and acidified sodium chlorite to reduce *Escherichia coli* O157 and *Salmonella typhimurium* in beef trim and ground beef in a simulated processing environment. *J Food Prot* 69:1802–1807
- Houghton PN, Lyng JG, Morgan DJ, Cronin DA, Fanning S, Whyte P (2011) Efficacy of high-intensity pulsed light for the microbiological decontamination of chicken, associated packaging, and contact surfaces. *Foodborne Patho Dis* 8:109–117
- Hierro E, Barroso E, LaHoz LD, Ordonez JA, Manzano S, Fernandez M (2011) Efficacy of pulsed light for shelf-life extension and inactivation of *Listeria monocytogenes* on ready-to-eat cooked meat products. *Innov Food Sci Emer Technol* 12:275–281
- Hinton AJ, Cason JA, Ingram KD (2002) Enumeration and identification of yeasts associated with commercial poultry processing and spoilage of refrigerated broiler carcasses. *J Food Prot* 65(6):993–998
- Hinton AJ, Northcutt JK, Smith DP, Musgrove MT, Ingram KD (2007) Spoilage microflora of broiler carcasses washed with electrolyzed oxidizing or chlorinated water using an inside-outside bird washer. *Poult Sci* 86:123–127
- Hudson J, Billington C, Premaratne A, On S. (2014). Inactivation of *Escherichia coli* O157:H7 using ultraviolet light-treated bacteriophages. *Food Sci Technol Int*. doi:10.1177/1082013214560445
- Hugas M, Garriga M, Monfort JM (2002) New mild technologies in meat processing: high pressure as a model technology. *Meat Sci* 62:359–371
- Jay J (2000) *Modern food microbiology*, 6th edn. Aspen Publishers, Inc, Gaithersburg, pp. 323–339
- Jean-Louis D, Sylvie C (2008) Meat quality assessment using biophysical methods related to meat structure. *Meat Sci* 80:132–149
- Jeong JY, Claus JR (2011) Color stability of ground beef packaged in a low-carbon monoxide atmosphere or vacuum. *Meat Sci* 87:1–6
- Jiang J, Xiong YL (2014) Technologies and mechanisms for safety control of ready-to-eat muscle foods: an updated review. *Crit Rev Food Sci Nutr*. doi:10.1080/10408398.2012.732624
- Jin T, Liu L, Sommers CH, Boyd G, Zhang H (2009) Radiation sensitization and postirradiation proliferation of *Listeria monocytogenes* on ready-to-eat deli meat in the presence of pectin-nisin films. *J Food Prot* 72:644–649
- Jofre A, Aymerich T, Grebol N, Garriga M (2009) Efficiency of high hydrostatic pressure at 600 MPa against food-borne microorganisms by challenge tests on convenience meat products. *LWT Food Sci Technol* 42:924–928
- Karabagias I, Badeka A, Kontominas MG (2011) Shelf life extension of lamb meat using thyme or oregano essential oils and modified atmosphere packaging. *Meat Sci* 88:109–116
- Keklik NM, Demirci A, Puri VM (2010) Decontamination of unpackaged and vacuum-packaged boneless chicken breast with pulsed ultraviolet light. *Poult Sci* 89:570–581
- Kim JW, Slavic MF (1996) Cetylpyridinium Chloride (CPC) treatment on poultry skin to reduce attached *Salmonella*. *J Food Prot* 59:322–326
- Kim BH, Jang A, Lee SO, Min JS, Lee M (2004) Combined effect of electron-beam (beta) irradiation and organic acids on shelf-life of pork loins during cold storage. *J Food Prot* 67:168–171
- King DA, Lucia LM, Castillo A, Acuff GR, Harris KB, Savell JW (2005) Evaluation of peroxyacetic acid as a post-chilling intervention for control of *Escherichia coli* O157:H7 and *Salmonella Typhimurium* on beef carcass surfaces. *Meat Sci* 69:401–407
- Kordowska-Wiater M, Stasiak DM (2011) Effect of ultrasound on survival of gram-negative bacteria on chicken skin surface. *Bull Vet Inst Pulawy* 55:207–210
- Kume T, Furuta M, Todoriki S (2009) Quantity and economic scale of food irradiation in the world. *Radioisotopes* 58:25–35
- Laury AM, Alvarado MV, Nace G, Alvarado CZ, Brooks JC, Echeverry A (2009) Validation of a lactic acid- and citric acid-based antimicrobial product for the reduction of *Escherichia coli* O157:H7 and *Salmonella* on beef tips and whole chicken carcasses. *J Food Prot* 72:2208–2211
- Lawrie RA, Ledward DA (2006) *Lawrie's Meat Science*, 7th edn. Woodhead Publishing Limited, Cambridge ISBN 978-1-84569-159-2
- Liao CH, Shollenberger LM, Phillips JG (2003) Lethal and sublethal action of acetic acid on *Salmonella* in vitro and on cut surfaces of apple slices. *J Food Sci* 68:2793–2798
- Loeffler M, McClements DJ, McLandsborough L, Terjung N, Chang Y, Weiss J (2014) Electrostatic interactions of cationic lauric arginate with anionic polysaccharides affect antimicrobial activity against spoilage yeasts. *J Appl Microbiol* 117:28–39
- Loretz M, Stephan R, Zweifel C (2010) Antibacterial activity of decontamination treatments for cattle hides and beef carcasses. *Food Control* 22:347–359
- Mani-Lopez E, Garcia HS, Lopez-Malo A (2012) Organic acids as antimicrobials to control *Salmonella* in meat and poultry products. *Food Res Int* 45:713–721
- Mariutti LRB, Nogueira GC, Bragagnolo N (2011) Lipid and cholesterol oxidation in chicken meat are inhibited by sage but not by garlic. *J Food Sci* 76:909–915

- Mastromatteo M, Lucera A, Sinigaglia M, Corbo MR (2009) Combined effects of thymol, carvacrol and temperature on the quality of non-conventional poultry patties. *Meat Sci* 83:246–254
- Mataragas M, Skandamis PN, Drosinos EH (2008) Risk profiles of pork and poultry meat and risk rating of various pathogen/product combinations. *Int J Food Microbiol* 126:1–12
- Milillo SR, Ricke SC (2010) Synergistic reduction of Salmonella in a model raw chicken media using a combined thermal and acidified organic acid salt intervention treatment. *J Food Sci* 75:121–125
- Ming X, Weber GH, Ayres JW, Sandine WE (1997) Bacteriocins applied to food packaging materials to inhibit *Listeria monocytogenes* on meats. *J Food Sci* 62:413–415
- Morey A, Bowers JWJ, Bauermeister LJ, Singh M, Huang T, McKee SR (2014) Effect of salts of organic acids on *Listeria monocytogenes*, shelf life, meat quality, and consumer acceptability of beef frankfurters. *J Food Sci* 79:54–60
- Morild RK, Christiansen P, Sørensen AH, Nonboe U, Aabo S (2011) Inactivation of pathogens on pork by steam-ultrasound treatment. *J Food Prot* 74:769–775
- Nychas GE, Skandamis PN, Tassou CC, Koutsoumanis KP (2008) Meat spoilage during distribution. *Meat Sci* 78:77–89
- Omer MK, Hauge SJ, Ostensvik O, Moen B, Alvseike O, Rotterud OJ, Prieto M, Dommersnes S, Nesteng OH, Nesbakken T (2015) Effects of hygienic treatments during slaughtering on microbial dynamics and contamination of sheep meat. *Int J Food Microbiol* 2:194–197
- Oreai M, Motalebi AA, Hoseini E, Javan S (2011) Effect of gamma-irradiation and frozen storage on microbial quality of rainbow trout (*Oncorhynchus mykiss*) fillet. *Iran J Fish Sci* 10:75–84
- Oussalah M, Caillet S, Salmieri S, Saucier L, Lacroix M (2004) Antimicrobial and antioxidant effects of milk protein-based film containing essential oils for the preservation of whole beef muscle. *J Agric Food Chem* 52:5598–5605
- Over KF, Hettiarachchy N, Johnson MG, Davis B (2009) Effect of organic acids and plant extracts on *Escherichia coli* O157:H7, *Listeria monocytogenes*, and *Salmonella typhimurium* in broth culture model and chicken meat systems. *J Food Sci* 74:515–521
- Park JH, Seok SH, Cho SA, Baek MW, Lee HY, Kim DJ, Chung MJ, Kim SD, Hong UP (2005) Antimicrobial effect of lactic acid producing bacteria culture condensate (LCCM) against *Salmonella enteritidis*. *Int J Food Microbiol* 101:111–117
- Paskeviciute E, Buchovec I, Luksiene Z (2011) High-power pulsed light for decontamination of chicken from food pathogens: a study on antimicrobial efficiency and organoleptic properties. *J Food Saf* 31:61–68
- Perumalla AVS, Hettiarachchy NS (2011) Green tea and grape seed extracts: potential applications in food safety and quality. *Food Res Int* 44:827–839
- Pohlman FW, Stivarius MR, McElyea KS, Waldroup AL (2002) Reduction of *E. coli*, *Salmonella typhimurium*, coliforms, aerobic bacteria, and improvement of ground beef color using trisodium phosphate or cetylpyridinium chloride before grinding. *Meat Sci* 60:349–356
- Ransom JR, Belk KE, Sofos JN, Stopforth JD, Scanga JA, Smith GC (2003) Comparison of intervention technologies for reducing *Escherichia coli* O157:H7 on beef cuts and trimmings. *Food Prot Trends* 23:24–34
- Rastogi NK (2010) Opportunities and challenges in nonthermal processing of foods. In: Passos ML, Ribeiro CP (eds) *Innovation in food engineering: new techniques and products*. CRC Press, USA, pp. 4–41
- Richardson SD (2003) Disinfection by-products and other emerging contaminants in drinking water. *TrAC Trends Anal Chem* 22:666–684
- Rojas MC, Martin SE, Wicklund RA, Paulson DD, Desantos FA, Brewer MS (2007) Effect of high-intensity pulsed electric fields on survival of *Escherichia coli* K-12 suspended in meat injection solutions. *J Food Saf* 27:411–425
- Sheen S, Hwang C, Juneja VK (2011) Modeling the impact of chlorine on the behavior of *Listeria monocytogenes* on ready-to-eat meats. *Food Microbiol* 28:1095–1100
- Sofos JN (2008) Challenges to meat safety in the 21st century. *Meat Sci* 78:3–13
- Sofos JN, Busta FF (2001) Chemical food preservatives. In: Russell AD, Hugo WB, Aycliffe GAJ (eds) *Principles and Practice of Disinfection, Preservation and Sterilization*, 2nd edn. Blackwell Scientific, Oxford
- Stopforth JD, Yoon Y, Belk KE, Scanga JA, Kendall PA, Smith G, Sofos JN (2004) Effect of simulated spray chilling with chemical solutions on acid-habituated and non-acid-habituated *Escherichia coli* O157:H7 cells attached to beef carcass tissue. *J Food Prot* 67:2099–2106
- Tamblyn KC, Conner DE (1997) Bactericidal activity of organic acids against *Salmonella typhimurium* attached to broiler chicken skin. *J Food Prot* 60(6):629–633
- Taylor S, Brock J, Kruger C, Berner T, Murphy M (2004) Safety determination for the use of bovine milk-derived lactoferrin as a component of an antimicrobial beef carcass spray. *Regul Toxicol Pharmacol* 39(1):12–24
- Theron MM, Lues JFR (2007) Organic acids and meat preservation: a review. *Food Rev Int* 23(2):141–158
- Tiwari BK, Valdramidis VP, O'Donnell CP, Muthukumarappan K, Bourke P, Cullen PJ (2009) Application of natural antimicrobials for food preservation. *J Agric Food Chem* 57:5987–6000
- Whyte P, Collins JD, McGill K, Monahan C, Mahony HO (2001) Quantitative investigation of the effects of chemical decontamination procedures on the microbiological status of broiler carcasses during processing. *J Food Prot* 64:179–183
- Xi Y, Sullivan GA, Jackson AL, Zhou GH, Sebranek JG (2012) Effects of natural antimicrobials on inhibition of *Listeria monocytogenes* and on chemical, physical and sensory attributes of naturally-cured frankfurters. *Meat Sci* 90:130–138
- Yang H, Kendall PA, Medeiros LC, Sofos JN (2009) Efficacy of sanitizing agents against *Listeria monocytogenes* biofilms on high-density polyethylene cutting board surfaces. *J Food Prot* 72:990–998
- Zhao T, Doyle MP, Kemp MC, Howell RS, Zhao P (2004) Influence of freezing and freezing plus acidic calcium sulfate and lactic acid addition on thermal inactivation of *Escherichia coli* O157:H7 in ground beef. *J Food Prot* 67:1760–1764
- Zhou F, Ji B, Zhang H, Jiang H, Yang Z (2007) Synergistic effect of thymol and carvacrol combined with chelators and organic acids against *Salmonella typhimurium*. *J Food Prot* 70:1704–1709
- Zhou GH, Xu XL, Liu Y (2010) Preservation technologies for fresh meat: A review. *Meat Sci* 86:119–128
- Zhu M, Du M, Cordray J, Ahn DU (2005) Control of *Listeria monocytogenes* contamination in ready-to-eat meat products. *Compr Rev Food Sci Food Saf* 4:34–42