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REVIEW

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

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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

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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 thermosphecta* (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 CO_2 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 microfloraYeast 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/cm^2, a mass equal to bacterial counts of 1×10^8 organisms/cm^2 (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, ClO_2) 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 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 handheld 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 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"?

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	• Formation of surface slime • Discoloration of products • Production of gas • Change in odor • Fat decomposition take place
Anaerobic bacteria	Absent	• Putrefaction and foul odors • Gas production • Results in souring of meat products
Yeasts	Present	• Surface slime formation • Discoloration occurs • Change in odor and taste • Decomposition of fat in meat
Molds	Present	• 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 uses125 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 occurs 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 decreased proton motive force (PMF) that can results 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-Ordonez 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/cm^2 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 2 % lactic acid and alginate dip	0.50 log reduction 0.74 log reduction	(Laury et al. (2009)
Lean beef and adipose tissues	1, 3, 5 % lactic, acetic, citric Pilot scale washer	1 to 2 log reduction	(Harris et al. 2006)
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 1 % acetic acid 1.5 % fumaric dip	0.78 log reduction 0.63 log reduction 1.96 log reduction	(Cutter and Siragusa 1996)

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 dehiding 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 sat by Australia and the EU members counties 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 (CO_2) 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 CO_2 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, CO_2 can be applied in meat industry for controlling the growth of microrganisms.

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 ombination 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 vaccum 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/cm^2. 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 possesese 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 bacterivorous* 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 sate 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/cm^2 and 1.5 log CFU/cm^2 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/cm^2 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.

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