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Review Preservation technologies for fresh meat – A review

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ABSTRACT

Fresh meat is a highly perishable product due to its biological composition. Many interrelated factors influence the shelf life and freshness of meat such as holding temperature, atmospheric oxygen (O₂), endogenous enzymes, moisture, light and most importantly, micro-organisms. With the increased demand for high quality, convenience, safety, fresh appearance and an extended shelf life in fresh meat products, alternative non-thermal preservation technologies such as high hydrostatic pressure, superchilling, natural biopreservatives and active packaging have been proposed and investigated. Whilst some of these technologies are efficient at inactivating the micro-organisms most commonly related to food-borne diseases, they are not effective against spores. To increase their efficacy against vegetative cells, a combination of several preservation technologies under the so-called hurdle concept has also been investigated. The objective of this review is to describe current methods and developing technologies for preserving fresh meat. The benefits of some new technologies and their industrial limitations is presented and discussed.

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1. Introduction

Meat is defined as the flesh of animals used as food. The term 'fresh meat' includes meat from recently processed animals as well as vacuum-packed meat or meat packed in controlled-atmospheric gases, which has not undergone any treatment other than chilling to ensure preservation. The diverse nutrient composition of meat makes it an ideal environment for the growth and propagation of meat spoilage micro-organisms and common food-borne pathogens. It is therefore essential that adequate preservation technologies are applied to maintain its safety and quality (Aymerich, Picouet, & Monfort, 2008). The processes used in meat preservation are principally concerned with inhibiting microbial spoilage, although other methods of preservation are sought to minimise other deteriorative changes such as colour and oxidative changes.

A number of interrelated factors influence the shelf life and keeping quality of meat, specifically holding temperature, atmospheric oxygen (O_2) , endogenous enzymes, moisture (dehydration), light and, most importantly, micro-organisms. All of these factors, either alone or in combination, can result in detrimental changes in the colour (Faustmann & Cassens, 1990), odour, texture and flavour of meat. Although deterioration of meat can occur in the absence of micro-organisms (e.g., proteolysis, lipolysis and oxidation), microbial growth is by far the most important factor in relation to the keeping quality of fresh meat (Lambert, Smith, & Dodds, 1991). Traditionally, methods of meat preservation may be grouped into three broad categories based on control by temperature, by moisture and, more directly, by inhibitory processes (bactericidal and bacteriostatic, such as ionising radiation, packaging, etc.), although a particular method of preservation may involve several antimicrobial principles. Each control step may be regarded as a 'hurdle' against microbial proliferation, and combinations of processes (so-called hurdle technology (HT)) can be devised to achieve particular objectives in terms of both microbial and organoleptic quality (Lawrie & Ledward, 2006).

The most investigated new preservation technologies for fresh meat are non-thermal inactivation technologies such as high hydrostatic pressure (HHP), new packaging systems such as modified atmosphere packaging (MAP) and active packaging (AP), natural antimicrobial compounds and biopreservation. All these alternative technologies attempt to be mild, energy saving, environmentally friendly and guarantee natural appearance while eliminating pathogens and spoilage micro-organisms. The aim of this article is to review these technologies for the preservation of fresh meat.

2. Refrigeration

Temperatures below or above the optimum range for microbial growth will have a preventative action on the latter. For fresh meat, refrigeration, including storage above or below the freezing point, has been the traditional preservation method. Superchilling technology, which stores meat just above the freezing point, has been used with success (Nowlan, Dyer, & Keith, 1974; Beaufort, Cardinal, Le-Bail, & Midelet-Bourdin, 2009).

2.1. Chilling

Recognition by early civilizations of the preservative effects of cool temperature storage of perishable products such as meat led to storage of such products in natural caves where temperatures were relatively low throughout the year. The principles of artificial ice formation and of mechanical refrigeration date from about 1750 (see Lawrie & Ledward, 2006) and commercial-scale operations based on mechanical refrigeration were in use 100 years later.

Chilling is critical for meat hygiene, safety, shelf life, appearance and eating quality. Chilling in air reduces carcass surface temperature and enhances carcass drying; both of which reduce the growth of bacteria (Ockerman & Basu, 2004). An increase in air velocity and/or a decrease in temperature (both controllable) decrease chilling time. A limiting factor, however, is the difficulty in removing heat quickly from the deeper tissue of carcasses.

Natural-convection air chilling, where refrigerant is pumped through cooling tubes, is slow and largely uncontrollable, whereas forced-convection air chilling, coupled with fans for air movement is much more efficient. Rapid carcass chilling increases product yield due to lower evaporation from the surface, while rapid drying of the carcass surface helps to reduce bacterial growth. Ultra-rapid chilling of pre-rigour meat may, on the other hand, lead to cold-shortening and toughening. Spray-chilling can enhance the oxygenation of surface myoglobin without increasing metmyoglobin, thus maintaining a bright appearance and eliminating weight loss (Feldhusen, Kirschner, Koch, Giese, & Wenzel, 1995).

2.2. Freezing

In Britain, large-scale preservation of meat by freezing commenced about 1880, when the first shipments of frozen beef and mutton arrived from Australia (Critchell & Raymond, 1969; Arthur, 2006). At that time, there was a surplus of meat animals in the southern hemisphere, especially in New Zealand and Australia, and freezing offered a means of preserving meat during the long voyages involved between the two areas (Critchell & Raymond, 1969). The advantages of temperatures below the freezing point were in prolonging the useful storage life of meat and in discouraging microbial and chemical changes (Lawrie & Ledward, 2006).

Fast freezing produces minute intracellular ice crystals and thus diminishes drip on thawing. The rate of freezing is dependent not only on the bulk of the meat and its thermal properties (e.g., specific heat and thermal conductivity), but also on the temperature of the refrigerating environment, on the method of applying the refrigeration and, with smaller cuts of meat, on the nature of the wrapping material used.

A temperature of -55 °C has been suggested as ideal storage conditions for frozen meat to completely prevent quality changes (Hansen et al., 2004). At these low temperatures, enzymic reactions, oxidative rancidity and ice recrystallisation are likely to be minimal and thus few deteriorative changes will occur during storage.

Cryogenic freezing offers faster freezing times compared with conventional air freezing because of the large temperature differences between the cryogen and the meat product and the high rate of surface heat transfer resulting from the boiling of the cryogen. Cryogenic freezing requires no mechanical refrigeration equipment; simply a cryogen tank and suitable spray equipment. However, there may be some distortion of the shape of the product caused by the cryogenic process that might impact on the commercial application. Furthermore, the cost of cryogenic liquid is relatively high and therefore may limit its commercial application. (Lovatt, James, James, Pham, & Jeremiah, 2004).

2.3. Superchilling

The process of superchilling was described as early as 1920 by Le Danois, even though he did not actually use the terms 'superchilling', 'deep-chilling' or 'partial ice formation'. The terms 'superchilling' and 'partial freezing' are used to describe a process where a minor part of the product's water content is frozen (Magnussen et al., 2008). During superchilling, the temperature of the product is lowered, often 1–2 °C, below the initial freezing point of the product. After initial surface freezing, the ice distribution equilibrates and the product obtains a uniform temperature at which it is maintained during storage and distribution (Magnussen et al., 2008). This has been effectively used for seafood (Olafsdottir, Lauzon, Martinsdottir, Oehlenschlager, &

Kristbergsson, 2006; Beaufort et al., 2009) and there is now increasing interest in this process for extension of chilled storage life of meat (Schubring, 2009).

2.3.1. Advantage and application

At superchilling temperatures, most microbial activity is inhibited or terminated. Chemical and physical changes may progress and, in some cases, even accelerate. Superchilling, as a commercial practice, can reduce the use of freezing/thawing for production buffers and thereby reduce labour, energy costs and product weight losses. The ice present in superchilled products protects the meat from temperature rises in poor cold chains; however, some increase in product drip loss may occur during storage (Magnussen et al., 2008).

'Super' or 'deep' chilling has been commonly used in the USA, although the product is seldom referred to as 'super-chilled' since, legally, in the USA poultry meat kept above -3.3 °C (26 °F) can be marketed as 'fresh' (US Poultry Products Inspection Regulations 9CFR381). The process involves water chilling of carcasses and then putting them through an air freezer operating at -15 °C for approximately 30 min. After packaging, they are again placed in an air freezer to achieve the required meat temperature. The carcasses are then stored and distributed at -1 to -2 °C.

The main reason for implementing this technology is its ability to prolong shelf life of meat for at least 1.4–4 times the life of traditional meat-chilling methods (Magnussen et al., 2008). Ice-forming and recrystallisation can cause microstructural changes to food tissue during freezing, resulting in cell dehydration, drip loss and tissue shrinkage during thawing. Food characteristics such as pH, ionic strength, concentration of dissolved gases, viscosity, oxidation-reduction potential and surface tension may also be altered, leading to changes in enzymic activity and protein denaturation (Cheftel, Levy, & Dumay, 2000).

Reports on superchilling have mainly involved fish (Beaufort et al., 2009) and poultry (Bogh-Sorensen, 1976). Gallart-Jornet et al. (2007) evaluated the effect of superchilled storage compared with ice and frozen storage on the quality of raw Atlantic salmon (Salmo salar) fillets and found superchilled storage was beneficial for the preservation of freshness of the raw material before processing. Duun, Hemmingsen, Haugland, & Rustad (2008) also found the storage time of vacuum-packed salmon fillets could be doubled by superchilled storage at -1.4 °C and -3.6 °C compared to ice chilled storage. Drip loss was not a major problem in superchilled salmon. Textural hardness was significantly higher in superchilled salmon fillets stored at -3.6 °C compared to those stored at -1.4 °C, ice chilled and frozen (Morkore, Hansen, Unander, & Einen, 2002; Hultmann, Rora, Steinsland, Skara, & Rustad, 2004). Cathepsins B and B+L remained active at the selected storage temperatures, which may therefore lead to softening during subsequent chilled storage.

Duun et al. (2008) found superchilling of pork roasts at -2.0 °C improved the shelf life significantly compared with traditional chilling at +3.5 °C. The superchilled roasts maintained good sensory quality and low microbiological counts during the whole storage period (16 weeks), while the shelf life of chilled samples was just 14 days. Sensory tests indicated that the quality of the superchilled roasts was not reduced by high numbers of psychrotrophic bacteria. The drip loss in superchilled samples was low and showed less variation than in the chilled references and the temperature-abused samples. The temperature-abused and chilled samples had lower liquid losses, measured by centrifugation, than the superchilled samples (Duun et al., 2008).

2.3.2. Challenges in superchilling

Calculating the required superchilling times and estimating the temperature distributions in a chilling and freezing process is a challenging exercise. It is also difficult to define the degree of superchilling required to sufficiently improve shelf life and fulfil the demands of the process to achieve the quality attributes desired (Magnussen et al., 2008).

The media used to achieve superchilling will affect the possibilities for implementing it in an industrial process. A change from 'traditional technologies' such as chilling, freezing, thawing to the more complex superchilling technology is difficult. Superchilling demands more accurate information on product variation and flow. Special care needs to be taken prior to, and after, the superchilling process itself. Most equipment producers today do not have the required energy and thermodynamic competence to design and control superchilling processes (Magnussen et al., 2008).

Clearly, industry will need support to develop basic data for graphs and software, of chilling times, chilling temperatures, air-flow and refrigeration loads. This also includes principles for control regulate monitor (CRM) systems for the superchilling process and refrigeration system (Magnussen et al., 2008).

3. Ionising radiation

lonising radiation has been a method of direct microbial inhibition for preserving meat since around 1940 (see Lawrie & Ledward, 2006). In 1980, participating bodies (including the Food and Agricultural Organization (FAO) and World Health Organization (WHO)) proposed that irradiation with a dose less than 10 kGy (1 Mrad) should be accepted as a process for preserving all major categories of food (WHO, 1981). In the UK, 'The Food (Control of Irradiation) Regulations (1990)' allows certain classes of food may be irradiated up to a maximum dosage (e.g., 7 kGy for poultry) and under 'The Food Labelling (Amendment)(Irradiated Food) Regulations (1990)' all irradiated foods are required to have a label indicating that they have received such treatment. Irradiation technology was promoted by the FAO in the Codex Alimentarius in 2003 and has been well accepted in 50 countries, especially in the USA, Egypt, China and across Latin America (Aymerich et al., 2008).

The radionuclides approved for food irradiation include ¹³⁷Cs and ⁶⁰Co. Radioactive cobalt (⁶⁰Co) decays to non-radioactive nickel by emitting high-energy particles and X-rays. The X-rays kill rapidly growing cells (microbes) but do not leave the product radioactive. Because it is highly penetrating, it can be used to treat packaged food (Brewer, 2009).

The advantages of ionising radiation for food preservation include its highly efficient inactivation of bacteria, the fact that the product is essentially chemically unaltered and the appreciable thickness of material, which can be treated after packing in containers (Lawrie & Ledward, 2006). A maximum dosage of 10 kGy represents a low amount of energy (equivalent to that needed to raise the temperature of 1 g water 2.4 °C), which is why the technology is considered nonthermal, thus preserving the freshness and nutritional quality of the meat and meat products when compared with thermal methods (Aymerich et al., 2008).

Colour changes in irradiated fresh meat occur because of the inherent susceptibility of the myoglobin molecule to energy input and alterations in the chemical environment; haem iron being particularly susceptible. Brewer (2004) summarised the effects of ionising radiation on meat colour, and concluded that maintenance of ideal meat colour during the process of irradiation could be enhanced by various combinations of pre-slaughter feeding of antioxidants to livestock, condition of the meat prior to irradiation (pH, oxymyoglobin vs. metmyoglobin), addition of antioxidants directly to the product, gas atmosphere (MAP) or lack thereof, packaging and temperature control (Brewer, 2004). Radiation treatment resulted in essentially no loss of thiamine (one of the least stable vitamins) (Graham, Stevenson, & Stewart, 1998), therefore suggesting that such radiation has no detrimental effects on these nutrients.

4. Chemical preservatives and biopreservation

4.1. Chemical preservatives

Carbon dioxide and ozone have been used to discourage the growth of surface micro-organisms on beef carcasses during prolonged storage at chill temperatures. Although ozone leaves no toxic residues in meat, its use in a production environment can be dangerous for personnel. Moreover, it accelerates the oxidation of fat and is more effective against air-borne micro-organisms than against those on meat (Lawrie & Ledward, 2006).

Various micro-organisms produce organic acids and alcohols by anaerobic fermentation of food substrates and these, by inhibiting other organisms that are concomitantly present and which could spoil the food or make it toxic, can act in its preservation. Lactic acid, for example, is a frequently effective inhibitory agent used in fresh meat preservation; however, other organic acids have also been found to be responsible for discolouration and production of pungent odours (Teotia, 1974).

Salts such as sodium lactate have been used in the meat industry because of their ability to increase flavour, prolong shelf life, and improve the microbiological safety of products (Diez, Santos, Jaime, & Rovira, 2009). The antimicrobial effects of lactates are due to their ability to lower water activity and the direct inhibitory effect of the lactate ion (Houtsma, Wit, & Rombouts, 1993; Koos & Jansener, 1995). Several researchers have successfully extended the shelf life of fresh meat products (Shelef, Mohammed, Wei, & Webber, 1997; Vasavada, Carpenter, Cornforth, & Ghorpade, 2003) by adding sodium lactate. Nadeem et al. (2003) extended freshly slaughtered sheep and goat carcasses stored at 5–7 °C for 3 and 2 days, respectively, after spraying the carcasses with solution 'B' containing potassium sorbate, sodium acetate, sodium citrate, sodium lactate each at 2.5% and sodium chloride at 5%, when compared with solution 'A' (without potassium sorbate) and control.

4.2. Biopreservation and natural antimicrobials

Natural compounds, such as essential oils, chitosan, nisin and lysozyme, have been investigated to replace chemical preservatives and to obtain 'green label' products. Storage life is extended and safety is increased by using natural or controlled microflora, of which lactic acid bacteria (LAB) and their antimicrobial products such as lactic acid and bacteriocins have been studied extensively. Bacteriocins are a heterogeneous group of antibacterial proteins that vary in spectrum of activity, mode of action, molecular weight, genetic origin and biochemical properties (Stiles & Hastings, 1991).

Various spices and essential oils have preservative properties and have been used to extend the storage life of meat products. These include eugenol in cloves and allyl isothiocyanate in mustard seed. Roller et al. (2002) and Sagoo, Board and Roller (2002) reviewed the antifungal and antimicrobial properties of the polysaccharide chitosan. Its efficacy, especially in combination with other antimicrobial agents, warrants further investigation.

Nisin is the only commercial bacteriocin and has been used to decontaminate artificially contaminated pieces of raw pork (Murray & Richard, 1997) and in combination with 2% of sodium chloride as an anti-listerial agent in minced raw buffalo meat (Pawar, Malik, Bhilegaonkar, & Barbuddhe, 2000). Bacteriocins produced by lactic acid bacteria are listed in Table 1.

Recently, pentocin 31-1, which was produced by *Lactobacillus pentosus* 31-1 and isolated from the traditional Chinese fermented Xuanwei ham, was studied as a biopreservative in storage of traypackaged chilled pork. Results showed that pentocin 31-1 could substantially inhibit the accumulation of volatile basic nitrogen (VBN) and generally suppress the growth of microflora, especially *Listeria*

Table 1

Bacteriocins produced by lactic acid bacteria (Adapted from Stiles & Hastings, 1991; Castellano, Belfiore, Fadda, & Vignolo, 2008).

Producer	Bacteriocin	Producer organism	Bacteriocin
organism			
L Lactis subsp	Nisin	Lh curvatus LTH1174	Curvacin A
lactis	110000		curraciii ii
L Lactis BB24	Nisin	Lh curvatus CRL705	Lactorin 705
L Lactis WNC	Nisin Z	Lb. curvatus FS47	Curvaticin FS47
L lactis subsp	Lacticin 481	Ib. curvatus 1442	Curvacin I 442
lactis	Luctient for	LD. Culvatas E 1 12	Curvaeni E i 12
I lactis subsp	Diplococcin	Th plantarum CTC305	Plantaricin A
cremoris	Diplococciii	LD. plantarum CrC505	i fulltui felli / f
L lactis subsp	Lactostrencins	Lc. gelidum UAL187	Leucocin A
lactis	Lactoberepenio	Der genaam en briefer	Deacoentin
L. lactis subsp.	Bacteriocin	Lc. mesenteroides	Leucocin A
diacetilactis	550	TA33a	
L. fermenti 46	ND	Lc. carnosum TA11a	Leucocin A
L. helveticus 27	Lactocin 27	P. acidilactici L50	Pediocin L50
L. helveticus	Helveticin J	P. pentosaceous Z102	Pediocin PA-1
L. acidophilus	Lactacin B	C. piscicola LV17B	Carnobacteriocin B2
L. acidophilus	Lactacin F	C. piscicola V1	Piscicocin vla
L. plantarum	Plantaricin A	C. piscicola LV17A	Carnobacteriocin A
L. sakei Lb 706	Sakacin A	C. piscicola JG126	Piscicolin 126
L. sakei 1151	Sakacin P	C. piscicola KLV17B	Carnobacteriocin B1/B2
L. sakei	Sakacin K, P	C. divergens 750	Divergicin 750
LTH673, 674		0	0
L. sakei CTC494	Sakacin K	C. divergens LV13	Divergicin A
L. sakei L 45	Lactocin S	E. faecium CTC492	Enterocin B
L. sakei MN	Bavaricin MN	E. faecium CTC492	Enterocin A
Lb. brevis SB27	Brevicin 27	E. casseliflavus	Enterocin 416K1
		IM416K1	
L. casei	Caseicin 80	P. acidilacticii PAC1.0	Pediocin PA1
P. acidilactic H	Pediocin AcH	P. pentosaceus FBB61	Pediocin A

and *Pseudomonas*, during chilled pork storage (Jinlan, Guorong, Pinglan, & Yan, 2010).

5. High hydrostatic pressure (HHP)

Derived from material sciences (ceramics, superalloys, artificial diamonds, etc.), high-pressure technology (100–1000 MPa, i.e., 1000–10 000 bar) is of increasing interest to biological and food systems (Cheftel & Culioli, 1997). High hydrostatic pressure (HHP), a non-thermal technology, is of primary interest because it can inactivate product-spoiling micro-organisms and enzymes at low temperatures without changing the sensory or nutritional characteristics of the product. Pressure processing is usually carried out in a steel cylinder containing a liquid pressure-transmitting medium such as water, with the sample being protected from direct contact by using sealed flexible packaging. Maintaining the sample under pressure for an extended period of time does not require any additional energy apart from that required to maintain the chosen temperature (Cheftel & Culioli, 1997).

HHP renders food more stable due to its ability to reduce the number of spoilage and pathogenic micro-organisms, and to inactivate certain food enzymes (Patterson, 2005). HHP is a powerful tool to control risks associated with *Salmonella* spp. and *Listeria monocytogenes* in raw or marinated meats (Hugas, Garriga, & Monfort, 2002). The effectiveness of HHP for microbial control depends on factors such as the process parameters, pressure level, temperature and exposure time, as well as by intrinsic factors of the food itself, such as pH, strain and growth stage of micro-organisms, and food matrix (Hugas et al., 2002; Garriga, Grebol, Aymerich, Monfort, & Hugas, 2004).

HHP, combined with moderate temperature, has been shown to result in changes in the mechanical properties leading to improved tenderness of meat (Cheftel & Culioli, 1997; Ma & Ledward, 2004; Sikes, Tornberg, & Tume, 2010). However, HHP even at low temperatures may have an undesirable effect on fresh meat colour. Colour of fresh beef (Carlez, Veciana-Nogues, & Cheftel, 1995; Jung, Ghoul & de Lamballerie-Anton, 2003) changes with pressure as a result of denaturation of globin in myoglobin and haem displacement or release, and ferrous oxidation (Mor-Mur & Yuste, 2003). Denaturation of other proteins such as myosin and actin results in a greater opacity and therefore minimises the red appearance. In contrast to beef and pork, poultry muscles are not drastically discoloured because of their lower myoglobin content (Hansen, Trinderup, Hviid, Darre, & Skibsted, 2003). Lipid stability of pressuretreated foods of animal origin has been little investigated, and results are contradictory (Orlien, Hansen, & Skibsted, 2000; Wiggers, Kroger-Ohlson, & Skibsted, 2004; Tume, Sikes, & Smith, 2010). Rivas-Cañedo, Fernández-García and Nuñez (2009) used high pressure (400 MPa, 10 min at 12 °C) to treat minced beef and chicken breast, which was packaged with or without aluminium foil in a multilayer polymeric bag. They found pressurisation produced significant changes in the levels of some volatile compounds presumably originating from microbial activity and the plastic material (Rivas-Cañedo et al., 2009). In the USA, several meat companies have made this methodology available (e.g., Hormel Foods and Purdue Farms) for the extension of shelf life of processed, sliced meats (Hugas et al., 2002).

Although the initial investment is high, the processing cost has been estimated at about 14 eurocent per kilogram of product when treated at 600 MPa, including investment and operation costs, and the technology is well accepted in Europe as an alternative technology (Aymerich et al., 2008). Table 2 lists some applications of HHP in meat products.

6. Packaging

Packaging protects products against deteriorative effects, which may include discolouration, off-flavour and off-odour development, nutrient loss, texture changes, pathogenicity and other measurable factors. Variables that influence shelf life properties of packaged fresh meat are product type, gas mixture, package and headspace, packaging equipment, storage temperature and additives.

Fresh meat packaging is only minimally permeable to moisture and so surface desiccation is prevented, while gas permeability varies with the particular film type used. Packaging options for raw chilled meat are air-permeable packaging, low O₂ vacuum, low O₂ MAP with anoxic gases and high O₂ MAP. While air-permeable packaging is not MAP, use of overwrapped packaging materials within master pack or tray-in-sleeve systems allows for this packaging option to be a component of MAP (McMillin, Huang, Ho, & Smith, 1999).

6.1. Vacuum packaging (VP)

Vacuum packaging materials for primal cuts are usually three layered co-extrusions of ethyl vinyl acetate/polyvinylidene chloride/ ethyl vinyl acetate, which generally have an O₂ permeability of less than 15.5 ml m⁻² $(24 h)^{-1}$ at 1 atmosphere as a result of the polyvinylidene chloride layer (Jenkins & Harrington, 1991). The lack of O₂ in packages may minimise the oxidative deteriorative reactions, and reduce aerobic bacteria growth, which usually causes pigments to be in the deoxymyoglobin state. Low O₂ vacuum packages for retail meat cuts are usually vacuum skin packaging (VSP) systems for placing the retail cut in a barrier styrene or polypropylene tray and vacuum sealing barrier films that are heat shrunk to conform to the shape of the product (Belcher, 2006). VSP packaging equipment removes atmospheric air or flushes the air from the package with gaseous mixtures such as N₂, CO₂ or mixtures of N₂ and CO₂ before heat sealing the film layers. The common construction for the top and bottom package webs is nylon barrier polymer of polyvinylidene chloride or ethylene vinyl alcohol, tie layer and ionomer. Nylon provides bulk, toughness and low melting point, while the barrier layer prevents vapour permeation and the ionomer gives necessary seal characteristics (Jenkins & Harrington, 1991). A variation of VSP is for the lidding film to have outer barrier and inner air-permeable layers so that before retail display, the outer barrier film layer is peeled away from the permeable layer so that air can then contact the meat product and result in a bloomed colour (Belcher, 2006; Jeyamkondan, Jayas, & Holley, 2000; Renerre, 1987).

6.2. Modified atmosphere packaging (MAP)

MAP for meat requires a barrier of either of moisture and gas permeation through packaging materials to maintain a constant package environment during storage. For any type of MAP, it is necessary to remove or change the normal composition of atmospheric air, and encompass both aerobic and anaerobic types of packaging for meat. The major gases in dry air by volume at sea level are N₂ (78%), O₂ (20.99%), argon (0.94%) and CO₂ (0.03%), but the percentages vary when calculated by weight (McMillin, 2008).

Low O_2 MAP has been readily available, but lesser used even though VP is the most cost-effective packaging (McMillin, 2008). Shrinkable film development for use on horizontal form-fill-seal equipment eliminates excessive film use, and wrinkles (Eilert, 2005). Low O_2 MAP may be used as a barrier package with an anoxic atmosphere of N_2 and CO_2 . N_2 is an inert gas that is not reactive with meat pigments or absorbed by the meat; therefore, it maintains integrity of the package by its presence in the headspace. However,

Table 2

Application of HHP in meat products (adapted from Aymerich et al (2008).

Target	Product	Initial counts	Reduction	Process ^a	Reference
		log (CFU/g)	log (CFU/g)		
FBP ^b	Meat homogenate	6-7	Total inactivation after treatment	400 MPa, 10 min, 25 °C	Shigehisa, Ohmori, Saito, Taji and Hayashi (1991)
C. freundii P. fluorescens L. innocua	Minced beef muscle	7	>5 after treatment	300 MPa 10 min, 20 °C 200 MPa 20 min, 20 °C 400 MPa 20 min, 20 °C	Carlez, Rosec, Richard and Cheftel (1993)
Total microflora	Minced beef muscle	~6.8	>4 after 10 days (3 °C)	450 MPa, 20 min, 20 °C	Carlez, Rosec, Richard and Cheftel (1994)
E. coli O157:H	Raw minced meat	5.9	5 after treatment	700 MPa, 1 min, 15 °C	Gola et al. (2000)
Aerobic total count	Marinated beef loin	6.5	>4.5 after 120 days (4 °C)	600 MPa, 6 min, 31 °C	Garriga, Aymerich, Costa, Monfort and Hugas (2002)
Toxoplasma gondii cysts	Ground pork meat	Viable tissue cysts	Non-viable	300 MPa	Lindsay, Collins, Holliman, Flick and Dubey (2006)
Salmonella enteritidis strains	Chicken breast fillets	7	4.8	400 MPa, 15 min, 12 °C	Morales, Calzada, Rodriguez, de Paz and Nunez (2009)

^aInitial temperatures are reported. ^b Escherichia. coli, Campylobacter jejuni, Pseudomonas aeruginosa, Salmonella typhimurium, Yersinia enterocolitica.

CO₂ reacts with meat, changing the properties as noted in the next section. Barrier trays are filled with product and then sealed with barrier lidding film after flushing with the desired gas mixture. The barrier tray is usually preformed off-site, but may be made on form-fill-seal packaging equipment where the web or base film is heated and drawn into the tray mould by a vacuum so product can be placed into the formed film cavity before heat sealing of barrier film to the top edges of the formed tray (Jenkins & Harrington, 1991). This process leads to the meat pigment being in the deoxymyoglobin state, which appears as a purple colour and may be unfamiliar to many consumers (Lynch, Kastner, & Kropf, 1986).

Non-barrier overwrapped packages of meat may be enclosed in a barrier pouch appropriately sized for each individual overwrapped tray package (tray-in-sleeve configuration), or in a larger barrier film master pack that contains multiple packages in the anoxic gas (McMillin et al., 1999). The meat pigments become oxygenated when the overwrapped permeable film package is removed from the master pack for retail display (Belcher, 2006). Another variation is the use of anoxic MAP that has an inner air-permeable film and outer barrier film sealed to the barrier tray or bottom web containing the meat. When the outer film is peeled before display, the meat is exposed to O₂ in the atmospheric air and subsequently blooms. Where air-permeable films may not allow sufficient O₂ passage for adequate oxymyoglobin formation, microperforated shrink films with additional holes or perforations have been manufactured and used to promote faster meat blooming after removal of barrier film or removal of overwrapped trays from master packs (Beggan, Allen, & Butler, 2005).

Carbon monoxide (CO) has also been used in low O_2 retail packaging systems. Meat may be exposed to CO before packaging or CO may also be used to gas flush VSP packages before sealing, but the small amounts of CO are still sufficient to impart a desired red meat colour (Belcher, 2006; Eilert, 2005; Sebranek, Hunt, Cornforth & Brewer, 2006). The majority of MAP for fresh meat has been with a high O_2 environment (around 80% O_2) that allows sufficient shelf life for processors and retailers with controlled distribution systems (Eilert, 2005).

6.3. Active packaging (AP)

AP is the incorporation of specific compounds into packaging systems that interact with the contents or environment to maintain or extend product quality and shelf life, while intelligent or smart packaging provides for sensing of the food properties or package environment to inform the processor, retailer and/or consumer of the status of the environment or food (Kerry, O'Grady & Hogan, 2006).

In AP, the primary active technologies mostly enhance the protection or shelf life of the product in response to interactions of the product, package and environment, although it may perform other functions. AP may also involve the deliberate altering of the package environment at a specified time or condition through passive or active means, but without the inputs and continuous monitoring needed with controlled atmosphere packaging (CAP) (Yanyun, Wells, & McMillin, 1994). Intelligent packaging systems have components that sense the environment and process the information and then allow action to protect the product by conducting communication functions (Yam, Takhistov, & Miltz, 2005).

AP functions and technologies include moisture control, O_2 permeable films, O_2 scavengers or absorbers, O_2 generators, CO_2 controllers, odour controllers, flavour enhancement, ethylene removal, antimicrobial agents and microwave susceptors (Brody, Bugusu, Han, Koelsch Sand, & McHugh, 2008; Brody, 2009) in addition to indicators of specific compounds (Vermeiren, Devlieghere, Beest, Kruijf, & Debevere, 1999) and temperature control packaging.

6.3.1. Antimicrobial packaging

One promising type of active packaging is the incorporation of antimicrobial substances in food packaging materials to control undesirable growth of micro-organisms on the surface of foods. Antimicrobial packaging is an extremely challenging technology that could extend shelf life and improve food safety in both synthetic polymers and edible films. The market volume for antimicrobial use in polyolefins is projected to increase from 3300 tons in 2006 to 5480 tons in 2012 (McMillin, 2008).

Antimicrobial films can be defined as four basic categories as follows (Cooksey, 2005): (1) Incorporation of the antimicrobial substances into a sachet connected to the package from which the bioactive substance is released during further storage. (2) Direct incorporation of the antimicrobial into the packaging film (Table 3). When applied in a hot extrusion material, thermoresistance and shearing resistance of the antimicrobial must be considered. (3) Coating of the packaging with a material that acts as a carrier for the additive. The substance will not be submitted to high temperature or shearing forces; moreover, it could be applied as the later step. (4) Antimicrobial macromolecules with film-forming properties.

Sachets include O_2 scavengers, CO_2 generators, chlorine dioxide generators, while bioactive agents dispersed in the packaging may be O_2 scavenging films, silver ions, triclosan, bacteriocins, spices, essential oils, enzymes and other additives (Coma, 2008). Extrusion of the antimicrobial agent into the film results in less product-toagent contact than application of the agent to the surface of the film. However, agents bound to the film surface are likely limited to enzymes or other proteins because the molecular structure must be large enough to retain activity on the micro-organism cell wall while being bound to the surface of the food. Slow migration of the

Table 3

Natural active components incorporated directly into polymers used for meat packaging.

Active component	Polymer/carrier	Substrate	References
Nisin	Silicon coating	Beef tissue	Daeschel, McGuire and Al-Makhlafi (1992)
	PE	Beef carcass tissue	Siragusa, Cutter and Willett (1999),
Lactic acid	Alginate	Lean beef muscle	Siragusa and Dickson (1992))
Tocopherol	LDPE	Beef	Moore, Han, Acton, Ogale, Barmore and Dawson (2003)
Rosemary extract	Polystyrene	lamb steaks	Camo, Beltrán and Roncalés (2008)
Thyme, rosemary and sage spice	Cross-linked caseinate and whey protein film	Ground beef	Balentine, Crandall, O'Bryan, Duong and Pohlman (2006)
Oregano extract	Polystyrene	lamb steaks	Camo et al. (2008)
Chitosan	Chitosan	Cooked ham	Ouattara et al. (2000)
Chitosan	Chitosan	Culture media - Listeria monocytogenes	Coma et al. (2002)
Triclosan	Plastic matrix	Food borne pathogenic bacteria and bacteria associated with meat surface	Cutter (1999)

Abbreviations: PE-polyethylene, LDPE-low density PE.

Table 4

Selected commercial antimicrobial packaging for food applications (adapted from Appendini & Hotchkiss, 2002; Devlieghere, Vermeiren & Debevere, 2004).

Active component	Tradename	Producer Company	Packaging forms for food applications
Allylisothio-cyanate	WasaOuro	Lintec Corp.	Sachets
Silver Zeolite	Aglon TM	Agion	Paper, plastics
Glucose oxidase (H ₂ O ₂)	Bioka	Bioka Ltd	Sachets
Triclosan	Microban	Microban prod.	Plastic packaging
Ethanol vapour	Ethicap	Freund	Sachets
	Oitech	Nippon Kayaku	Sachets
Carbon dioxide	Freshpax [™]	Multisorb technologies	Sachets
	Verifrais	SARL Codimer	
Chlorine dioxide	Micro-sphére	Bernard Technologies	Sachets, film, wraps, plastics

antimicrobial agents to the product surface improves efficiency and helps maintain high concentrations. Packages with headspace require volatile active substances to migrate through the headspace and gaps between the package and food (Quintavalla & Vicini, 2002). Some food-related antimicrobial packaging applications have been commercialised (Table 4).

6.3.1.1. Potential antimicrobial agents. Antimicrobial substances are defined as biocidal products under EU Directives, but would only be permitted in food packaging if there were no direct impact on the packaged food quality. This requires that agent migration into food must be incidental rather than intentional, the agent could not provide a preservative effect to the food and the agent could not allow selection of biocide resistance in micro-organisms (Quintavalla & Vicini, 2002). Potential antimicrobial agents for use in food packaging systems are organic acids, acid salts, acid anhydrides, para-benzoic acids, alcohol, bacteriocins, fatty acids, fatty acid esters, chelating agents, enzymes, metals, antioxidants, antibiotics, fungicides, sterilising gases, sanitising agents, polysaccharides, phenolics, plant volatiles, plant and spice extracts and probiotics (Cutter, 2006). Antimicrobial compounds that have been evaluated in film structures are organic acids and their salts, enzymes, bacteriocins, triclosan, silver zeolites and fungicides (Quintavalla & Vicini, 2002). Triclosan, at 500 and 1000 mg kg⁻¹ in low density polyethylene (LDPE) films, exhibited antimicrobial activity against pathogenic bacteria in agar diffusion assay, but did not effectively reduce micro-organism growth on chicken breast meat in VP at 7 °C (Vermeiren, Devlieghere, & Debevere, 2002).

Bioactive surface coatings on packaging materials might have activity based on migration or release by evaporation into headspace and may be bacteriocins, spices or essential oils (Coma, 2008). Examination of four polyethylene films differing in ethylene vinyl acetate and erucamide content, and coated with three different bacteriocins, showed antimicrobial activity against most of the indicator strains, with antimicrobial agent distribution and roughness of the film related to activity of the packaging (Storia, Ercolini, Marinello, & Mauriello, 2008).

One of the most promising fields is the incorporation of antimicrobials such as bacteriocins and plants extracts to the active packaging and their association to biodegradable packaging such as alginate, zein (natural) or synthetic polyvinyl alcohol (PVA) to reduce wastes and also, being environment friendly (Aymerich et al., 2008).

Antimicrobial agents such as nisin and chlorine dioxide have shown effectiveness against bacteria but further technical developments are needed for commercial implementation (Cooksey, 2005). Fast- and slow-release ClO_2 sachets reduced total plate counts by 1– 1.5 logs in packages of chicken breast meat after 15 days, with no offodour detected by sensory panelists, but the colour of chicken 6.3.1.2. Sensors and indicators. Many intelligent packaging systems use sensors and indicators for a variety of measurements including fluorescence-based O₂ gas detection, temperature monitoring, toxic compounds, freshness through monitoring of specific components, package integrity and product identification (Kerry et al., 2006; De Kruijf, van Beest, Rijk, Sipilaeinen-Malm, Paseiro-Losada, & de Meulenaer, 2002; Potter, Campbell, & Cava, 2008).

stability of myoglobin and beef steaks by inhibition of metmyoglobin

and lipid oxidation (Nerin et al., 2006).

A colour-changing sensor was accurately related to the concentrations of amines (microbial breakdown products) in package headspace, and was also correlated to changes in non-pathogenic microbial populations of fish (Pacquit et al., 2007).

The formation of volatile amines in chicken meat during chilled storage in air packaging, VP and MAP with 30% CO₂:5% O₂ was highly related to total microbial counts and negatively with sensory taste scores, suggesting that biosensors for the volatiles might be developed to indicate spoilage in chicken (Balamatsia, Patsias, Kontominas, & Savvaidis, 2007). However, food pathogen levels were not related to microbial and sensory spoilage traits in ground beef patties in high O₂ MAP and low O₂ MAP with 0.4% CO or in chicken in low O₂ with 0.4% CO because food spoilage is defined collectively by factors such as storage temperature, package atmosphere, light intensity, meat constituents, initial microbial loads, endogenous enzyme activity and consumer perceptions that are ineffective to growth and survivability of food pathogens under controlled conditions (Brooks et al., 2008).

6.3.1.3. Bioactive edible coatings. Bioactive edible coatings incorporate an antimicrobial compound in an edible coating, applied by dipping or spraying onto the food. Edible coatings of polysaccharides, proteins and lipids can improve the quality of fresh, frozen and processed meat and poultry products by, for instance, delaying moisture loss, reducing lipid oxidation and discolouration, enhancing product appearance and functioning as carrier of food additives (Gennadios, Hanna, & Kurth, 1997). The applications of bioactive edible coating in fresh meat preservation are summarised in Table 5.

6.3.1.4. Future research of AP. As might be surmised from previous sections of this article, further research is needed in most areas regarding meat-packaging materials, selection of meat and its handling before packaging, meat properties under differing conditions, meat in packaging systems and integration of the different logistical components of the cold chain.

The key research needs for MAP of meat are as follows: (1) Characterisation of each MAP option – biochemical effects on

Table 5	
Applications of bioactive edible coati	ng in fresh meat preservation.

Bioactive edible coating	Substrate	References
Agar coatings	Fresh poultry	Natrajan (1997)
	Cold smoked salmon	Neetoo, Mu and Haiqiang (2010)
Calcium alginate gels	Raw beef	Siragusa et al. (1999)
Milk protein-based	Beef muscle	Oussalah, Caillet, Salmieri,
edible film		Saucier and Lacroix (2004)

appearance and palatability traits, including postmortem tenderisation processes, and interactions with each MAP system; interactions of meat components with packaging materials, gases, and headspace volumes; blooming ability and bloomed colour stability. (2) Additional and improved methodologies for evaluation of meat and meat products - inadequate or imprecise analytical techniques for meat in MAP, particularly with multistage systems; techniques not sufficiently rapid for continuous process and quality control programs; expensive or unavailable scanning and digital technologies for analytical or online meat assessment. (3) Pigment chemistry data - creation and reversion of deoxymyoglobin pigments under different conditions of MAP; formation and stability of carboxymyoglobin under different conditions; fundamental relationships between metmyoglobin reduction and O₂ consumption processes. (4) Roles of genetics and quantitative trait loci - genetic inheritance of colour and other meat traits are not well characterised. (5) Application of AP technologies for meat - improved petroleum and biological polymers have not been examined for use in meat packaging; no reports of micro-organism growth, oxidative stability, package gas concentrations, and other shelf-life factors for many meat and package interactions. (6) Nanotechnologies and nanoscale materials: improved mechanical, thermal and barrier properties of materials would enhance meat guality and shelf life; methods, materials, safety evaluations, and risk assessments for meat use have not been reported. (7) Clinical trials on specific product and packaging interactions and components insufficient or unavailable information on many MAP systems creates reliance on inferences for assessments of safety and risk (McMillin et al., 1999; Mancini, Hunt, Hachmeister, Kropf, & Johnson, 2005; McMillin, 2008).

7. Hurdle technology (HT)

HT (also called combined methods, combined processes, combination preservation, combination techniques or barrier technology) advocates the deliberate combination of existing and novel preservation techniques to establish a series of preservative factors (hurdles) to improve the microbial stability and the sensory quality of foods as well as their nutritional and economic properties (Leistner & Gorris, 1995; Leistner, 2000).

The most important hurdles used in food preservation are temperature (high or low), water activity (*a*), acidity (pH), redox potential (Eh), preservatives (e.g., nitrite, sorbate, sulphite), and competitive micro-organisms (e.g., lactic acid bacteria). However, more than 60 potential hurdles for foods, which improve the stability and/or quality of the products, have been described, and the list of possible hurdles for food preservation is by no means complete (Leistner & Gorris, 1995). The influence of food preservation methods on the physiology and behaviour of micro-organisms in foods, that is, their homeostasis, metabolic exhaustion and stress reactions, should be taken into account.

Generally, biopreservation and natural antimicrobials provide an excellent opportunity for such combined preservation systems. For example, oregano essential oil, combined with MAP, were studied as hurdles in the storage of fresh meat and a longer shelf life was observed over that of the same packaging alone (Skandamis & Nychas, 2002; Chouliara, Karatapanis, Savvaidis, & Kontominas, 2007). In Atlantic salmon (*S. salar*) fillets, the greatest extension of shelf life was obtained by a combination of superchilling and MAP. The samples with the highest CO_2 concentration (90%) and gas-to-product volume (g/p) ratio of 2.5 showed the highest shelf life: 22 days versus 11 days for the control sample (Fernández, Aspe, & Roeckel, 2009).

Many studies indicate that it is possible to reduce bacterial spores through combinations of mild heat (Hayakawa, Kanno, Tomita, & Fujio, 1994; Ross, Griffiths, Mittal, & Deeth, 2003) or nisin (Michiels, Hauben, Versyck, & Wuytack, 1995; Stewart, Dunne, Sikes, & Hoover, 2000; Garriga et al., 2002; Lee, Heinz, & Knorr, 2003; Jofre, Aymerich & Garriga, 2008; Ogihara, Yatuzuka, Horie, Furukawa, & Yamasaki, 2009) and HHP. The combined effect of gamma irradiation in the presence of ascorbic acid on the microbiological characteristics and lipid oxidation of ground beef coated with an edible coating were evaluated. Results showed that lactic acid bacteria and *Brochothrix thermosphacta* were more resistant to irradiation than *Enterobacteriaceae* and *Pseudomonas*. Shelf-life extension periods estimated on the basis of a limit level of 6 log CFU g⁻¹ for APCs were 4, 7 and 10 days for samples irradiated at 1, 2 and 3 kGy, respectively. However, the incorporation of ascorbic acid in ground beef did not improve significantly (p>0.05) the inhibitory effect of gamma irradiation (Lacroix, Ouattara, Saucier, Giroux, & Smoragiewicz, 2004).

8. Conclusion

This review aimed to describe current methods and technologies for fresh meat preservation and their developments. In addition to the relatively mature technologies, such as chilling, freezing and ionising radiation, new preservation techniques for fresh meat are introduced. We conclude this review by presenting important opportunities and some drawbacks of the following new techniques.

- Superchilling can reduce the use of freezing/thawing for production buffers and thereby reduce labour, energy costs and product weight losses. The other two advantages of the technique are its capability for prolonging shelf life and improving meat safety. However, the major drawback is that complex calculations and measurements of heat transfer and temperatures are required for each product. More research is required before the wide application of this new technology. Furthermore, this process will only function effectively with improved cold chains, as many current meat supply chains are comprised of fragmented components rather than logical cold chain systems.
- 2. As a mild, non-thermal technology, HHP can inactivate some product spoilage micro-organisms and enzymes at low temperatures without changing the majority of the sensory or nutritional properties. However, spores are not sensitive to these pressures and they can only be inactivated when pressure is combined with heat or another system such as lactoperoxidase or lysozyme treatment. Although HHP has certain advantages, it does however have some drawbacks in that high pressures may result in discolouration through protein denaturation. Further, commercially it involves a batch process, which is not convenient for product handling.
- 3. Active packaging: This technique is attractive to producers as oxygen scavengers in sachets are effective and enables surface treatment of food products. As it incorporates compounds into packing systems to maintain or extend product quality and shelf life, it can facilitate processing. However, when oxygen scavengers are incorporated in packaging films, as distinct from packet sachets, their effectiveness is often limited. Efforts have to be made to make this technique compatible with current legislation. Usually, the amounts of active compound migrating are not substantial. In addition, active compounds need to be thermostable when incorporated in plastic films.
- 4. Natural antimicrobial compounds: Essential oils, chitosan, nisin and lysozyme are natural compounds. As they can replace chemical preservatives, they provide the opportunity for 'Green labelling' to which consumers are attracted by their 'natural image'. This is imperative in the current world environment in which food quality and safety food are of prime importance. Nevertheless, they are often less attractive commercially due to their ability to react with other food ingredients and some may have low water solubility. They can also change the organoleptical properties and have a narrow activity spectrum.

In conclusion, by applying these new technologies to meet increased demand, the storage life of fresh chilled meat can be largely extended to many weeks by proper control of the hygienic condition and temperatures of the product, and by the appropriate selection and use of preservative methods. Factors restricting the commercial extension of shelf life are the current processing and distribution systems.

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