# Current Practice and Innovations in Meat Packaging

| | |
|---|---|
| **Project code:** | 2014/1046 |
| **Prepared by:** | Zhongxiang Fang, Yanyun Zhao, Min Zhang |
| **Date submitted:** | 20 April 2015 |
| **Date published:** | XXX |
| **Published by:** | XXX |

# Table of Contents

## 1.0   Introduction

There is a growing demand by consumers for foods perceived as natural, fresh-tasting, nutritious, healthy and safe, including meat and meat products (Grunert & Valli, 2001; Morrissey, Sheehy, Galvin, Kerryh, & Buckleyh, 1998). A consumer survey carried out in six European countries indicated that "colour", "flavour" and "freshness" are the most important intrinsic quality cues for meat before purchase, after purchase, and food safety perception, respectively (Glitsch, 2000). All these quality and safety properties are highly dependent on meat packaging materials and technologies. Due to greater stringency in national and international hygiene and safety standards for fresh and processed meat products, with ever-increasing demands by retailers for cost-effective extensions to product shelf-life and the requirement to meet the above consumer expectations, the meat packaging industry has rapidly developed in the past decade (Kerry, O'Grady, & Hogan, 2006).

It was reported that packaging has become the third largest industry in the world and it represents about 2% of Gross National Product (GNP) in developed countries (Han, 2005; Robertson, 2005). The fundamental reasons for packaging fresh and processed meat products are preventing contamination, delaying spoilage, permitting some enzymatic activity to improve tenderness, reducing weight loss, and retaining colour and aroma (Brody, 1997; Mondry, 1996). Based on this, the current meat packaging practices range from overwrap packaging for short-term chilled storage and/or retail display, to vacuum packaging, bulk-gas flushing or modified atmosphere packaging (MAP) systems for long-term chilled storage, each with different attributes and applications (Kerry, O'Grady, & Hogan, 2006).

Recently, a series of new packaging technologies and materials have been developed including active packaging, intelligent packaging, edible coatings/films, biodegradable packaging, and nanomaterial packaging. These technologies and materials have the potential to improve the quality and safety, prolong the self-life, reduce the environment impact, and increase the attractiveness of the packaged product to the retailers and consumers, outcomes that are favourably welcomed by the food industry. However, only a limited number of these technologies are relevant to meat and meat product packaging applications and there is also limited comprehensive reviews in this area, with the latest one being published more than 5 years ago (Egan, Eustace, & Shay, 1988; Quintavalla, & Vicini, 2002; Kerry, O'Grady, & Hogan, 2006; Coma, 2008; McMillin, 2008). The Australian red meat industry is composed of approximately 25 million cattle and 120 million sheep, which brings it the world's largest exporter of beef (23% of total world exports) and the second largest exporter of sheep meats (42% of total world exports) (Pointon, Jenson, Jordan, Vanderlinde, Slade, & Sumner, 2006).

The red meat and meat production is also the No. 1 economic contributor to Australian farm and fisheries food production, with a value about 13.6 billion Australian dollars in the 2011-2012 financial year (DAFF, 2013). Research developments in the meat packaging technology area are progressing rapidly broadening potential applications. This comprehensive review will examine the world packaging systems currently being used for meat and meat product application, and assess new and developing technologies that may have potential for commercial use in meat packaging system into the future. The internationally registered patents in the last 15 years will also be reviewed and discussed. The global regulatory aspects of these technologies with a focus on the regions of USA, European Union and Asia, which should be seriously considered by Australia meat processing stakeholders, will also be investigated in this review.

## 2.0 Food quality and safety issues in meat packaging and potential solutions

### 2.1 Meat colour

Colour is the first impression of meat and meat products that influences consumer purchasing decision and affects their perception of the freshness of the product. The colour of meat may vary from the deep purplish-red of freshly cut beef to the light grey of faded cured pork, depending on the concentration and status of a coloured pigment of myoglobin in the muscle. The greater the concentration of myoglobin, the darker is the colour of the meat. For example, beef is red whereas pork is much paler and this is partly due to beef containing about nine times as much myoglobin as pork (Egan, Eustace, & Shay, 1988). During the storage and processing of meat, the myoglobin is reversibly converted into oxymyoglobin or metmyoglobin in the presence or absence of oxygen respectively, consequently resulting in different meat colours (Figure 1). Undoubtedly the most important colour change is the loss of redness in meat caused by the formation of metmyoglobin, and green sulphmyoglobin caused by bacterial spoilage, such as in vacuum packed primal joints with high pH and slight oxygen permeability of the packaging material (Taylor & Shaw, 1977). In processed meat products, for example frankfurters, ham and bologna sausage, the contamination of lactic acid bacterial may also cause greening because of the formation of a green pigment of choleglobin (Egan, Eustace, Shay, 1988). Meat packaging and storage should follow procedures to prevent/minimize the adverse reactions/changes for the meat to remain the desirable colour. This is the fundamental to select appropriate technologies/materials to store/pack fresh and processed meats.
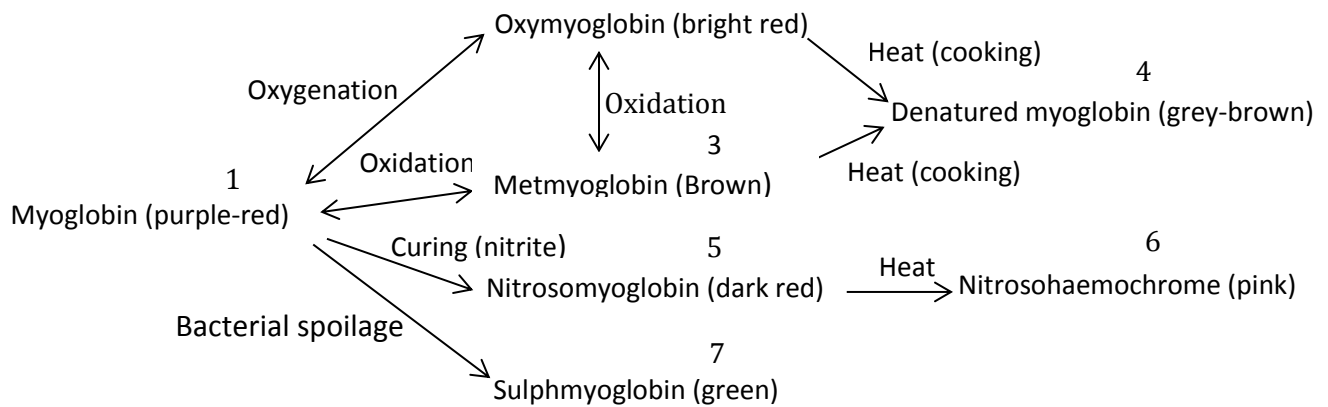


1, vacuum packed beef; 2, fresh beef stored in air; 3, "Stale' fresh meat stored in air; 4, cooked fresh meats; 5, non-cooked cured meats (raw hams); 6, cooked cured meats (cooked hams); 7, bacterial spoiled meats.

**Figure 1. The forms and colours of myoglobin in different types of meat and meat products (modified from Egan, Eustace, & Shay, 1988)**

## 2.2.    Lipid oxidation

Lipid oxidation is another major cause of quality deterioration in meat and meat products, which is manifested by adverse changes in flavour, colour, texture and nutritive value, and possible production of toxic compounds (Gray, Gomaa, & Buckley, 1996). Lipid oxidation is believed to be a complex process whereby unsaturated fatty acids reacting with molecular oxygen via a free radical chain mechanism form peroxides. This process is initiated when a labile hydrogen atom is abstracted from a site on the fatty acyl chain, with the production of a free lipid radical which reacts rapidly with oxygen to form a peroxyradical, which abstracts a hydrogen atom from another hydrocarbon chain yielding a hydroperoxide and a new free radical that perpetuates the chain reaction (Enser, 1987). The primary auto-oxidation is followed by a series of secondary reactions which lead to the degradation of the lipid and the development of oxidative rancidity, and consequently result in flavour deterioration, decrease in nutritional and texture values, and may have safety issues (Ladikos, & Lougovois, 1990).

Fatty acid oxidation in meat and meat products is influenced by the animals' diet (e.g. vitamin E supplementation); fat composition, metals, haem compounds and salts in meats; and the packaging, processing and storage materials and methods (Morrissey, Sheehy, Galvin, Kerryh, & Buckleyh, 1998). In terms of packaging technology, the most obvious precaution to take against oxidative deterioration is to remove the air, such as by wrapping raw meat in oxygen-impermeable films, vacuum packaging or modified atmosphere packaging (carbon dioxide and nitrogen), or addition of free radical/oxygen scavengers/inhibitors in the packaging materials as will be discussed in detail later.

## 2.3    Microbial contamination

Food Standards Australia New Zealand (FSANZ) assessed that fresh meat from domestically reared cattle, sheep, goats and pigs present only a low risk to public health, whereas the health risks presented by ready-to-eat manufactured meats and meat products is relatively higher (FSANZ, 2009). Fresh raw meat from healthy animals contains few microorganisms. During handling, storage and processing, the surface of the carcass might be contaminated with microorganisms from the hide/fleece, equipment (e.g. knives), and the hands and clothes of the workers, or even cross-contamination of other foods and water with pathogens of animal origin.

In a microbiological risk profile study of the Australian red meat industry (Sumner, Ross, Jenson, & Pointon, 2005), "high" risk hazard–product pairings were identified as meals contaminated with Clostridium perfringens provided by caterers with no implementation of HACCP; kebabs cross-contaminated by Salmonella present in drip trays or served undercooked; meals served in the home cross-contaminated with Salmonella. "Medium" risk hazard–product pairings were identified as ready-to-eat meats contaminated with Listeria monocytogenes; Uncooked comminuted fermented meat (UCFM)/salami contaminated with enterohaemorrhagic E. coli (EHEC) and Salmonella; undercooked hamburgers contaminated with EHEC; kebabs contaminated by Salmonella under normal production or following final "flash" heating. Identified "low" risk hazard–product pairings were cooked, ready-to-eat sausages contaminated with Salmonella; UCFM/salami contaminated with L. monocytogenes; well-cooked hamburgers contaminated with EHEC.

In the European Union, the most frequently pathogens in meat were Campylobacter and Salmonella, followed by Yersinia spp., Escherichia coli, and L. monocytogenes (Nørrung & Buncic, 2008). The most serious meat safety issues resulting in immediate consumer health problems and recalls from the USA marketplace are associated with microbial pathogens of E. coli O157:H7 and Salmonella in fresh meat

products and Gram-positive L. monocytogenes in ready-to-eat meat and poultry products (Sofos, 2008). Obviously, the microbial safety of meat is a world-wide concern. As meat spoilage is the outcome of environmental conditions and the microbial interaction (Tsigarida, Boziaris, Nychas, 2003), meat microbial safety issues could be minimized or eliminated if the conditions described in the following sections are optimized during storage and processing.

### 2.3.1    Temperature

Temperature is the most important extrinsic factor that influences the sensory property (e.g. colour, flavour), nutritional quality (e.g. protein and lipid degradation) and safety (eg the growth of microorganisms) in meat and meat products (Koutsoumanis, Stamatiou, Skandamis, & Nychas, 2006). In practice, all meat and meat product processing and storage should be maintained in a low temperature environment. The growth rates of most microorganisms at 0-1 °C are only about half those at 5 °C and further reduced as temperature falls, therefore a transportation and storage temperature for meats as low as practical (depending on the meat product and circumstance) should be used (Egan, Eustace, Shay, 1988). For example, because the freezing point of fresh meat is about -1.5 °C, the optimum storage temperature for non-frozen fresh meats should be about -1 °C, at which the bacterial growth is extremely slow and the chemical and biochemical changes occur at a minimum rate, and consequently an optimum shelf life will be achieved (Egan, Eustace, Shay, 1988). Meat packaging technology is most effective in improving meat quality and safety when the storage and transportation temperature is considered within the system.

### 2.3.2    Gas atmosphere

The growth of microorganisms in meat and meat products may be inhibited by modifying the gas composition surrounding them. The technology of modified atmosphere packaging (MAP) has been developed and applied in a wide range of fresh and processed foods to extend their shelf life, where the packaging environment atmosphere has been modified so that its composition is different to that of air (Wolfe, 1980). Generally, the gas composition is modified by increasing the level of carbon dioxide and/or reducing that of oxygen, and nitrogen is used as an inert filler gas either to reduce the proportions of the other gases or to maintain pack shape (Bell & Bourke, 1996). It was estimated that MAP can increase the shelf-life of meat and poultry by 50–400%, mainly because carbon dioxide ($CO_2$) has a bacteriostatic effect on gram negative spoilage organisms, and concentrations as low as 10–20% of the atmosphere effectively inhibit the growth of meat spoilage bacteria (Rao & Sachindra, 2002). Fresh red meats are typically stored in modified atmosphere packages containing 80% $O_2$:20% $CO_2$ (Georgala & Davidson, 1970) and cooked meats are stored in 70% $N_2$:30% $CO_2$ (Smiddy, Papkovsky, & Kerry, 2002). MAP also improves meat colour and flavour by decreasing the oxygen concentration in the packaging that in turn reduces the oxidation of pigments and fatty acids in the meat (McMillin, 2008). More detailed information in MAP of meats will be presented in section 3. Current practice in meat packaging.

### 2.3.3    Meat pH

The muscle pH in the living animal is neutral but becomes acidic (< 7) after death, which is caused by the conversion of glycogen to lactic acid by a glycolysis process (Egan, Eustace, Shay, 1988). The concentration of glycogen in animals determines the production of lactic acid and in turn the pH of the meat. Twenty four hours after slaughtering of unstressed animals, the usual pH (pH24) of the meat is about 5.5 and a pH24 of greater than 5.5 is thought to be the result of pre-slaughter glycogen depletion (Kannan, Chawan, Kouakou, & Gelaye, 2002). As summarized by Mach, Bach, Velarde, & Devant (2008), the main problems

of meat pH24 above 6.0 are a dark red colour, increased tenderness variation, poor palatability, and growth of microorganisms to unacceptable levels with development of off-odours and slime formation.

Whist most microorganisms can grow over the range of meat pH values of 5.4-7.0, higher pH permits more rapid growth of spoilage bacterial, especially in the presence of oxygen (Egan, Eustace, Shay, 1988). Therefore, to improve meat quality and microbial safety, it is important to reach a pH24 of 5.5 in the meat by avoiding glycogen depletion in animals. which is dependent on animal pre-slaughter physical exhaustion and psychological stress, such as time and handling from farm to slaughterhouse, waiting time at slaughterhouse, climatic factors, and the slaughter environment (Mach, Bach, Velarde, & Devant, 2008). Meat packaging technology is applied in post-slaughter and no direct influence on the pH of freshly slaughtered meats, therefore an effective meat packaging strategy should be designed to maintain the meat pH in the optimum range.

### 2.3.4   Water activity

Microorganisms need water to grow, and the growth rates are reduced as water content is reduced. Water activity (aw) is the ratio of vapour pressure of water in a food and the vapour pressure of pure water at the same temperature and pressure conditions, which specifies the amount of available or "active" water in a food (Labuza 1968). Microorganisms can only grow in a certain level of aw and the minimum aw at which important spoilage and pathogenic microorganisms can grow are present in Table 1. The aw of fresh carcass meat is 0.99 (Egan, Eustace, & Shay, 1988), suggesting most spoilage and pathogenic microorganisms can grow on the fresh meats. However, after processing (e.g. curing, smoking), the aw in meat products (e.g. ham, salami) is changed (decreased in ham and salami) which is a barrier to the growth of some microorganisms depending on their species (e.g. Table 1). In terms of the effect of meat aw on packaging material, it is well known that different packaging films have significantly different water vapour transmission rates, which may alter the moisture content and aw of meats during storage (Ščetar, Kurek, & Galić, 2010). To maintain the freshness of meat, packaging material should have minimum moisture permeability to prevent surface desiccation (Faustman & Cassens, 1990).

**Table 1: Minimum water activity for the growth of various microorganisms (adapted from Egan, Eustace, Shay, 1988; Gould, Measures, Wilkie, & Meares, 1977)**

| Microorganisms | Water activity |
|---|---|
| *Xeromyces bisporus* | 0.60 |
| *Saccharomyces rouxii* | 0.65 |
| *Halobacterium* | 0.74 |
| *Aspergillus flavus* | 0.75 |
| *Staphylococcus aureus* | 0.84 |
| Yeasts | 0.87 |
| *Escherichia coli, Pediococcus, Micrococcus* | 0.90 |
| *Lactobacillus, Streptococcus* | 0.93 |
| *Closteridium botulium, Escherichia, Salmonella* | 0.95 |

### 2.3.5 Chemical and biochemical inhibitors

During processing of meats, various ingredients are added to enhance the taste/flavour of meat products while also altering the microbial flora. For instance, sodium chloride (salt) is usually added at a specific level in processed meats to prevent the growth of Pseudomonas (Egan, Eustace, & Shay, 1988) and nitrite or nitrite alternatives are used in cured meats to inhibit the growth of C. botulinum (Pierson, Smoot, & Robach, 1983). Recently, antimicrobial packaging has been developed by either incorporating antimicrobial substances into a sachet connected to the package, by directly incorporating the antimicrobial agents into the packaging film, or by coating the packaging with a matrix that acts as a carrier for the antimicrobial agents (Cooksey, 2001).

The agents being incorporated in antimicrobial packaging include bacteriocins (e.g. pediocin PA-1 and lacticin 3147), spices and essential oils (e.g. oregano and garlic oil), enzymes (e.g. lysozyme) and preservatives and additives (e.g. acetic acid, lactic acid, potassium benzoate) (Coma, 2008). The microbial stability of the meats and meat products in the antimicrobial packages is significantly improved and their shelf life is prolonged. More information about the antimicrobial packaging will be discussed in section 4.1 Active packaging in meat industry.

## 3.0 Current Practice in Meat Packaging

Fresh meat usually refers to the muscle from a recently slaughtered animal (mainly cattle, goat, pig in this review) which has not undergone any process other than chilling (Zhou et al., 2010). It has high water content (about 75%) and abundant nutrients and thus is perishable. Packaging is one of the preservation technologies which protects foods including meat from adversary environmental factors that would otherwise cause quality degradation, and provides convenience for transportation and a communication link between consumer and food processor; thus expanding the supply chain and retail markets (Marsh and Bugusu, 2007; Barlow and Morgan, 2013).

Fresh packed meat has been one of the major meat products in the market since early in the 1900's (Cerisuelo et al., 2013). Vacuum packaging (VP) and modified atmosphere packaging (MAP) along with refrigeration, have become increasingly popular preservation techniques to extend the shelf life of meat and meat products, which have brought major changes in storage, distribution, and marketing of raw and processed meat products (Özogul et al., 2004; Cachaldora et al., 2013).

Packaging materials can provide physical, chemical and biological barriers against external factors, such as light, air, moisture, microorganism, insect, rodent, and mechanical damage. Currently, the most common materials used in food packaging are glass, metal (eg. aluminum, aluminum foil, tinplate, tin-free steel, and laminates and metallized films), plastics (including polyolefin, polyester, polystyrene, polyamide, ethylene vinyl alcohol, laminates and co-extrusions), paper and paperboard (Marsh and Bugusu, 2007). Plastics in particular are very popular in meat packaging, which can have different properties of strength, clarity, sealability and permeability to moisture and gases (Taylor, 1994). Selection of appropriate packaging films is critical to both the preservation effectiveness and also the cost (Muller, 1990).

Packaging delays meat quality deterioration such as microbial proliferation, discoloration, off-flavor, and nutrient loss (Zhou et al., 2010). Apart from air-permeable packaging, the most investigated packaging technologies for fresh and minimally processed meat are VP, MAP, and other novel methods like active packaging and intelligent packaging. Currently in the Australian market, meat and meat products are generally packed in thermoforming plastics in the following ways (Table 2) (AUS-MEAT, 2015).

This section of the review will describe the current applications and innovations in thermoforming film packaging, vacuum packaging and modified atmosphere packaging for meat and meat products. Other packaging techniques like active packaging and intelligent packaging will be discussed later in this review.

**Table 2: Packaging methods and symbols for Australian meat (adapted from AUS-MEAT, 2015)**

| Packaging methods | Symbols | Description | Photo examples |
|---|---|---|---|
| Individually wrapped | IW | Meat cut has been individually wrapped in an approved material, such as a sheet, stock netting or bag. These are most commonly used on larger primal cuts. | |
| Layer packed | LP | Product is packed into a carton containing two or more layers of meat with each layer separated by an approved material. Layer packed meat is most commonly used to layer small cut items (e.g. flank steaks or backstraps). | |
| Multi wrapped | MW | Meat has been packed in a single bag or covering and contains two or more cut items. This method is most commonly used for small and medium sized primal cut items (e.g. chuck tenders – lamb racks) | |
| Tray packed | TP | Meat is packed into an open container or tray, and covered with a film. This is mainly used in smaller primal cuts or portioned meat. | |
| Modified atmosphere packed | MAP | Packs (primal cuts or retail ready tray) are wrapped and are flushed with a mixture of gases to remove or lower the oxygen. | |
| Vacuum Packed | VP | Air and oxygen are removed from the packaging. Vacuum packing is adapted to all methods of packaging listed above except MAP. | |

## 3.1    Thermoforming films

Consumers prefer easy open and re-closeable packages to keep meat fresh because they take up less space in the refrigerator, and are relatively more environmentally friendly than tubs and cartons. Plastic polymers are most commonly used for meat packaging due to their low cost and good physical properties for industrial applications, such as light weight, excellent formability and flexibility. These thermoplastic synthetic polymers can be melt-processed by simply applying heat and shear (Mensitieri et al., 2011). The majority of packaging films used for meat and poultry are made of polyamides, polyolefins and polyesters (Arvanitoyannis and Stratakos, 2012).

### 3.1.1    Polyamide film

Polyamides (PAs), i.e. nylons, consist of large carbon chains (>6), which contribute to their high strength and resistance to puncture, abrasion and tearing (Mullan and McDowell, 2003). PA films are thermally stable and flexible at low temperatures and have resistance to dilute acids and alkalis (Robertson, 2006).

Mono or multilayer films based on PAs (like PA-6) are widely applied for packaging meat and meat products (e.g. sausage) under vacuum and modified atmosphere conditions (Félix et al., 2014). Additionally, multilayer films based on PA-6 are usually used for heating treatment during food processing because of the good heat resistance property.

### 3.1.2 Polyolefin film

Polyolefins are the major plastic materials for development of thermoforming films. Examples of polyolefins include polypropylene (PP), polystyrene (PS), polyvinyl chloride (PVC), and various grades of polyethylenes (HDPE, LDPE, etc.) (Duncan, 2011).

**(1) Polyvinyl chloride film**

Polyvinyl chloride (PVC) film is commonly used in packaging of fresh meats. The advantages of PVC film in meat packaging are its relatively high-oxygen permeability which favors the contact between the meat surface and oxygen, promotes the reaction with meat myoglobin and residual blood hemoglobin to form oxymyoglobin and oxyhemoglobin, respectively, and thus helps develop an attractive bright red color (Landrock and Wallace, 1955). Furthermore, it is relatively inexpensive and easy to use, due to good heat sealability. However, PVC film also has some disadvantages in meat packaging, such as highly susceptible to tearing and punctures leading to a high frequency of "leaky" packages; and bacterial growth and browning due to pigment oxidation leading to short shelf life (Cornforth and Hunt, 2008).

**(2) Polyethylene film**

Polyethylene (PE) film is also widely used in meat packaging. It has high elasticity, good heat sealablility, sufficient water vapor barrier properties and resistance to low temperatures, acids (except for nitric acid) and alkalis (Piringer and Baner, 2000). High density polyethylene (HDPE) has relatively poor $O_2$ permeability (200-400 nmol m-1 s-1 GPa-1), but has good water vapour barrier properties. Low density polyethylene (LDPE) has low permeability to water vapor but high permeability to gases. For example, LDPE could be easily penetrated by essential oils and escape from the package (Greengrass, 1999), which should be considered if essential oils are used as antimicrobial agents in LDPE packed meat. It was noted that the strength of polyethylene could be improved by co-extrusion with polyamide (Cornforth and Hunt, 2008). The co-extruded polyamide-polyethylene films are typically used for high-oxygen modified atmosphere packaging because of the goog oxygen barrier property (Sørheim et al., 1999).

### 3.1.3 Polyester films

Polyester is a category of polymers containing the ester functional group in their main chain, and most commonly refers to polyethylene terephthalate (PET); although there are many other types of polyester such as polylactic acid (PLA) and polybutylene terephthalate (PBT). PET films provide good resistance to high amd low temperatures, have high mechanical strength, medium-high oxygen barrier properties ($O_2$ permeability of 6-8 nmol m-1 s-1 GPa-1), and are easy to print-on by ink (Coles et al., 2003); therefore PET is widely used in meat packaging.

### 3.1.4 Other films

Other thermoforming film materials that can be applied for meat packaging include ethylene-vinyl alcohol (EVOH), polystyrene (PS), linear low-density polyethylene (LLDPE), polypropylene-oriented polypropylene (OPP), ethylene vinyl acetate (EVA), and polyvinylidene chloride (PVdC), each having different mechanical and barrier properties. However, pure individual polymers generally do not exhibit all of the desired

mechanical and barrier properties required for effective meat packaging applications. One of the major trends in thermoforming film packaging is that of flexible multilayer plastic films which can meet more technical requirements. For example, two multi-layered plastic films, called medium barrier (MB) comprising PP/tie/PA6/tie/PA6/tie/LDPE and high barrier (HB) where the central adhesive (tie) layer is replaced by a layer of EVOH, have been developed to improve the film oxygen barrier property, and the film mechanical and optical properties were also improved by the multi-layered formulation (Crippa et al., 2007).

There is also a significant push in the packaging material industry to develop monolayer films with enhanced mechanical and gas barrier properties and mono/multilayer films with better properties against microbial spoilage and quality deterioration, such as active and intelligent packaging film, nano-materials and biopolymers for packaging film, which will be discussed in the later in this review.

## 3.2 Vacuum packaging

Vacuum packaging (VP) is the packaging of a product in containers (rigid or flexible), from which air has been substantially removed before final sealing (Muller, 1990). Refrigerated processed meats like sausages, hot dogs and restructured ham products, and other sliced processed meats are traditionally vacuum-packed in plastic packages to minimize contact of the product with the oxygen and consequently prolong their shelf life. VP can also be considered as a variation of MAP, since the removal of normal atmosphere from package is a modification of the atmosphere (Rao and Sachindra, 2002).

### 3.2.1 VP materials

Vacuum packages for retail meat products are generally low O2 packaging systems in which the meat is in a barrier styrene or PE films and the heat-shrinkable barrier films are vacuum sealed to conform to the shape of the product (Belcher, 2006). Common materials for vacuum packaging include PA, EVA, EVOH and PET-PVdC. It should be noted that the reduced thickness at the corners of the package significantly affects the gas barrier properties of the vacuum package. Oliveira et al. (2006) suggested the use of EVOH in vacuum packaging because this material does not affect the gas barrier properties of the packaging corners. Currently, a typical VP material is usually a three layered co-extrusion of EVA/PVdC/EVA with O2 permeability of less than 15.5 ml m$^{-2}$ (24 h)$^{-1}$ at 1 atmosphere (Jenkins and Harrington, 1991). A variation of the VP system is using composite films with outer barrier and inner air-permeable layers. The outer barrier layer is peeled away from the permeable layer before retail display so that air can then contact the meat product causing a bloomed color (Belcher, 2006; McMillin, 2008; Zhou et al., 2010).

### 3.2.2 Current practice of VP in meat packaging

Vacuum packaged meats have been marketed successfully for years in many countries, as meat preservation under vacuum is generally very effective (Jeremiah, 2001; Jayas and Jeyamkondan, 2002). VP can be applied in both fresh meat and processed meat product packaging. The purple color of vacuum packaged meat is not considered as a significant drawback since the meat color returns to its desirable red color by contacting available oxygen at the surface after opening of the package. Recently, Avilés et al. (2014) compared the color stability of beef steaks under VP and re-packaging after leaks. Results showed that the color stability was reduced after repeated VP and thus should be avoided in practice.

Some examples of recent practice in vacuum meat packaging are presented in Table 3, which shows different film materials with different oxygen barrier properties have been used. According to references, some precautions are required during VP, including (Rao and Sachindra, 2002):

(1) Thorough evacuation of air and lessened water addition in order to prevent growth of aerobic spoilage organisms and protect the meat against undesirable shrinkage, oxidation, and color changes.

(2) Control of seam or slip closures for maintaining the vacuum condition. This will reduce the possibility of meat browning due to metmyoglobin formation during storage, owing to the presence of residual oxygen in the package, either through the barrier film or due to a leak in the package.

(3) Use of appropriate barrier film. The packaging film parameters depend on the correct selection of packaging materials and system. For instance, one VP method is using a very high barrier film to prevent growth of aerobic spoilage organisms, shrinkage and oxidation, and thus achieves extension of shelf-life. However, this method causes purple (deoxygenated) meat color and the dark-purplish color of deoxymyoglobin in vacuum packaged retail beef has not been widely accepted by US consumers (Meischen et al., 1987; Cornforth and Hunt, 2008). Another method is using an oxygen-permeable film (e.g. PVC film) allowing exposure of the meat surface to oxygen. This packaged meat has a red "bloom" color, which is desirable for consumers, but has a disadvantage of short shelf-life.

**Table 3: Some examples of recent practice in vacuum meat packaging**

| Meat materials | Packaging materials | Storage | References |
|---|---|---|---|
| Dry-cured Iberian ham | Laminated film (a mixture of polyamide and polyethylene, oxygen transmission rate: 38 $cm^3/m^2/24$ h/atm, Viduca, S.L., CASTALLA, ALICANTE, Spain). | 4±1°C, 120 days | Parra et al., 2010 |
| Beef and pork | Commercial barrier bags (oxygen transmission rate of 40-50 $ccm^{-2}$ 24 $h^{-1}$; used in Winpak Ltd., Winnipeg, MB, Canada) | -1.5°C or 4.0°C, 6 weeks | Balamurugan et al., 2011) |
| Beef | Plastic barrier film (low-density polyethylene, CRYOVAC BB3050, oxygen transmission rate: 0.83 $cm^3m^{-2}$ $h^{-1}$ at 23°C, used in CRYOVAC Sealed Air S.r.l., Milan, Italy) | 4°C, 20 days | Pennacchia et al., 2011 |
| Horse meat | Commercial barrier bags (oxygen transmission rate of 50 $cm^3/m^2/24$ h/bar at 23°C and 75% RH; water vapor transmission rate of 2.6 $g/m^2/24$ h at 23°C and 85% RH, used in TECNOPACK, Barcelona, Spain). | 2°C, more than 14 days | Gomez and Lorenzo, 2012; Lorenzo and Gomez, 2012 |
| "Morcilla", a typical cooked blood sausage | Commercial barrier bags (oxygen transmission rate of 50 $cm^3/m^2/24$ h/bar at 23°C and 75% RH; water vapor transmission rate of 2.6 $g/m^2/24$ h at 23°C and 85% RH, used in TECNOPACK, Barcelona, Spain). | 4°C, 8 weeks | Cachaldora et al., 2013 |

(4) The storage conditions for the VP meat are normally at low illumination and chilled temperatures, for example, 0-2°C for sliced meats, 3-6°C for whole meat goods, and 5-6°C for smoked and cured products. Vacuum packaging and storage at controlled temperatures of -1°C is widely used for fresh meat storage (Balamurugan et al., 2011).

### 3.2.3 Current developments of VP for meat and meat products

**(1) Development of novel vacuum packaging films**

The low oxygen conditions under vacuum packaging can minimize oxidative deterioration of meat and inhibit aerobic microbial growth. However, the residual oxygen may still turn myoglobin into deoxymyoglobin (Zhou et al., 2010) since only minimal time of exposure to 0.5-2% O2 may cause this browning (McMillin, 2008). To improve the VP meat color quality, vacuum packaging using nitrite-embedded film (NEF) has been used to extend fresh beef color display life (Claus and Du, 2013). However, this packaging technology has the potential to deposit residual nitrite in the meat, which may be a safety concern. As regulated by the USDA, nitrite can be used to cure meat at the levels of 120 to 200 ppm with 10 to 50 ppm residual nitrite at the meat at retail sale (Aberle, et al. 2012). It was observed that the amount of nitrite level embedded in the film of less than 2 ppm of the packed beef resulted in no measurable residual nitrite (Siegel, 2011), although residual nitrite (1.8 ppm) and nitrate (15.4 ppm) levels were found in the surface of the similar NEF packaged fresh beef (Claus and Du, 2014). Therefore, the addition of nitrite in the films should be well controlled to achieve the regulated nitrite residual level.

**(2) Synergistic effect of vacuum packaging with antioxidant/antimicrobial agents**

Many natural extracts such as essential oils from edible and medicinal plants, herbs and spices have been shown to possess antioxidant and antimicrobial functions and could serve as a source for active agents against food spoilage and deterioration (Dorman and Deans, 2000; Bagamboula et al., 2004). Using a combination of 1.0% pomegranate peel extract with vacuum packaging, Devatkal et al. (2014) observed a synergistic protective effect in cold stored goat meat on the quality parameters of texture, color, lipid oxidation and microbial total plate counts.

**(3) Modeling of microbial growth in vacuum-packaged meat and meat products**

To predict the microbial growth in vacuum packaged meat and meat products, Ye et al. (2013) developed a molecular predictive model using real-time polymerase chain reaction (PCR) methods to describe the growth of L. monocytogenes strains in vacuum-packaged chilled pork during storage at different temperature conditions. Compared with the conventional microbiology methods, the application of the molecular predictive approach was able to establish models of specific pathogens more accurately in the presence of other bacteria, and also save time and labor because this is much quicker than the conventional methods.

## 3.3 Modified atmosphere packaging

Modified atmosphere packaging (MAP) is a very important and practical preservation technique applied for extending shelf life of food, especially for fresh or minimally processed foods including meats, that allows the retention of their "fresh" character (Rao and Sachindra, 2002; Sandhya, 2010). In this technique, the air in the package is removed and exchanged with a gas of different composition that can inhibit growth of spoilage microorganisms and assist in maintaining high quality. MAP can thus extend the shelf-life of meat by 50-400%, especially at chill temperatures (Rao and Sachindra, 2002). In addition, Zakrys et al. (2009) reported that MAP beef steaks were preferred by consumers because of their increased tenderness and juiciness compared with steaks packaged in traditional tray packaging. The initial headspace environment of MAP may change due to reactions of the meat and microorganisms during storage without any additional manipulation of the internal gas composition and humidity (McMillin, 1996). In contrast with MAP, controlled atmosphere packaging (CAP) always maintains the same environmental conditions within the package by continuous monitoring and controlling gas atmosphere and humidity (McMillin, 2008). MAP at chill temperatures has been widely applied for red meats packaging, storage and transportation (Jeremiah, 2001), but CAP is more often used for packaging

of fruits and vegetables (Prince, 1989). Since ss earlier as the 1930s, MAP technique has been applied for transoceanic shipment of fresh meat from Australia and New Zealand to Great Britain. This technique is still commonly used today to extend meat shelf life and maintain high product quality.

### 3.3.1 Functions of different gases used in MAP

The most commonly used gases in MAP are oxygen ($O_2$), carbon dioxide ($CO_2$), and nitrogen ($N_2$). Carbon monoxide (CO) is also widely applied to meat packaging, especially red meat, although, relatively high costs, complicated standardisation of the gas mixture for each type of product and safety concerns have limited its application (Farber, 1991). Other gases such as argon (Ar), sulphur dioxide ($SO_2$) and nitrous and nitric oxides have also been investigated in meat packaging, but they have not been commercially applied mainly because of the potential safety issues and high costs (Sandhya, 2010).

**(1) Carbon dioxide**

The use of carbon dioxide as a bacteriostatic agent increases the shelf life of MAP meat (Jayas and Jeyamkondan, 2002). $CO_2$ can retard the growth of aerobic microorganisms by extending both the generation time and the lag phase of spoilage organisms due to the ability of intra-cellular pH changes. For example, concentrations as low as 10-20% $CO_2$ could effectively inhibit the growth of most spoilage bacteria in meat, such as S. aureus, Salmonella spp., E. coli, and Y. enterocolitica (Rao and Sachindra, 2002). This effect increases as the temperature decreases (Hintlian and Hotchkiss, 1986). A previous work by Vergara and Gallego (2001) showed that highly enriched carbon dioxide atmospheres (20-80% $CO_2$) also extended the shelf life of fresh lamb meat. However, in some MAP application, pack collapse may occur due to the high solubility of $CO_2$ in water (1.57 g/kg at 100 kPa, 20°C) causing the reduction of headspace volume (Sandhya, 2010).

**(2) Oxygen**

Oxygen accelerates some deteriorative reactions in foods like fat oxidation, pigment oxidation and browning reactions, and promotes growth of most common spoilage bacteria and fungi (Sandhya, 2010). In meat packaging, $O_2$ may promote rapid metmyoglobin formation, causing browning of fresh meat (Egan et al., 1988). Therefore, the pack atmosphere of most meats should maintain a low concentration of residual oxygen. However, a minimum concentration of about 5% $O_2$ is needed to maintain oxymyoglobin formation (Ledward, 1970). Furthermore, the $O_2$ can reduce the risk of anaerobic growth and toxin production in red meat, so selection of an appropriate oxygen level is a critical factor to keep the high quality of MAP meat.

**(3) Nitrogen**

Nitrogen is a relatively inert gas which neither supports the growth of aerobic microorganisms nor inhibits the growth of anaerobic bacteria. In MAP, sufficient $N_2$, due to its low solubility in water (0.018 g/kg at 100 kPa, 20°C) (Sandhya, 2010), can prevent pack collapse caused by $CO_2$ going into solution and $O_2$ being consumed by the aerobic microbes inside package (McMillin, 2008).

**(4) Carbon monoxide**

Carbon monoxide (CO) has been used in low $O_2$ MAP or VP because low concentrations of CO contribute to a desired pink-red colour in packaged red meat (Sebranek et al., 2006; Belcher, 2006; Zhou et al., 2010). This is because 0.4% or higher concentrations of CO in anaerobic packaging will induce carboxymyoglobin formation (red colour) (Cornforth and Hunt, 2008). Some research shows CO can also prevent the growth of pathogenic bacteria and to some extent reduce lipid oxidation in meat (Bornez et al., 2009) due to decreasing the redox potential in the package (Mancini and Hunt, 2005). The FDA has approved the use

of CO for meat packaging (US FDA, 2004), though this development has not been without controversy as some consumers concern its safety issue (Wilkinson et al., 2006).

**(5) Noble gases**

The noble gases of helium (He), argon (Ar), xenon (Xe) and neon (Ne) have been investigated in some food MAP applications due to their lack of reactivity. However, it seems to be difficult to find advantages of noble gases compared with $N_2$ used in meat packaging field because of their high costs.

In summary, the main functions of the gases used in MAP are to: 1) suppress bacterial growth ($CO_2$); 2) inhibit aerobic/prevent anaerobic microorganism growth ($O_2$); 3) retain meat color ($O_2$ and CO); 4) prevent oxidation of fats and pack collapse ($N_2$) (Chouliara et al., 2007). These gases can be applied individually or in combination to achieve an optimum effect.

### 3.3.2   Gas compositions for fresh and processed meat MAP

In MAP of meat and meat products, gas composition and storage temperature are two important factors associated with the product quality and shelf-life. A stable low temperature (eg. 4°C) decreases muscle tissue respiration rate and increases $O_2$ solubility at the meat surface (McMillin, 2008). Fluctuations in temperature (e.g. 0-4°C and 4-10°C) should be avoided as they may induce a more complex bacterial diversity in the meat compared with storage at a fixed temperature of 4°C (Zhang et al., 2012).

**(1) Low O2 MAP**

High carbon dioxide levels (10-80%) with the remainder being an inert gas (e.g. $N_2$) are commonly applied for MAP of meat and meat products in order to inhibit growth of aerobic microbes and extend shelf life (Kerry et al., 2006). Generally, about 20-30% $CO_2$ is enough to prevent aerobic spoilage bacteria (Sørheim et al., 2004). High $O_2$ concentrations promote the formation of red color pigment of oxymyoglobin, but negatively impact on the oxidative stability of muscle lipids and result in the development of oxidative rancidity and undesirable flavors (Bingol and Ergun, 2011).

Based on the microbiological, physical, chemical and the sensory properties of cooked meat, Fernandes et al. (2014) concluded that the 100% $CO_2$-MAP lamb loin samples had greater stability and better shelf life than those of VP and 75% $O_2$+25% $CO_2$-MAP products, though with less preferred for color quality. Another study also observed that high $CO_2$ MAP samples (60% $CO_2$+40% $N_2$) with no oxygen in the package resulted in the lowest lipid oxidation value during the storage of the cooked blood sausage "morcilla" (Cachaldora et al., 2013). Some examples of recent research in low $O_2$ MAP for meat are showed in Table 4, which indicated that the gas conditions can be optimized for different meat packaging.

**Table 4: Some examples of recent research in low O2 MAP for meat**

| Meat material | Low $O_2$ gas composition | Control | Storage | References |
|---|---|---|---|---|
| Lamb loins | 100% $CO_2$ | Vacuum; 75% $O_2$ + 25% $CO_2$ | 1±1°C; 28d | Fernandes et al., 2014 |
| Long-term chilled lamb loins (vacuum-packed and stored at -1.5°C for 9 wk) | 20% $CO_2$ + 80% $N_2$ | 80% $O_2$ + 20% $CO_2$ | 4°C, 7d under light | Kim et al., 2013 |
| Cooked blood sausage | 60% $CO_2$ + 40% $N_2$ | Vacuum; 15% $O_2$+ 35% $N_2$+ 50% $CO_2$; 60% $N_2$ + 40% $CO_2$ | 4°C, 8wk | Cachaldora et al., 2013 |

The absence or low concentrations of O2 in low O2 MAP or VP should minimize oxidative deterioration of packed meat and meat products. However, this technique usually causes pigments to be in the deoxymyoglobin state, resulting in a purple meat color (McMillin, 2008). Fortunately, this purple color meat will bloom when the meat is exposed to O2 in the atmospheric air due to the change of deoxymyoglobin to oxymyoglobin.

**(2) High O2 MAP**

It is well known that oxygen-free storage increases the risk for growth of anaerobic bacteria, such as Clostridium species (Moorhead and Bell, 1999). High O2 MAP has been therefore proposed for fresh meat packaging, where headspaces of 25-90% O2 + 15-80% CO2 may be used, with 70-80% O2 + 20-30% CO2 is the most frequently used gas composition (Gill, 1996; Buys et al., 2000; Eilert, 2005).

Esmer et al. (2011) reported that minced beef had acceptable color, oxidation stability and microbial loads in 14-day storage under MAP with modified atmosphere gas compositions 50% O2+30% CO2+20% N2. Poultry meat is also regularly stored in MAP with high oxygen concentrations (Eilert, 2005). Blacha et al. (2014) showed that high-oxygen packaging (80% O2, 20% CO2) had a small advantage on color, lipid oxidation and sensory quality for storage of turkey breast muscle cutlets compared with vacuum and other MAP conditions (80% N2+20% CO2 and 20% O2+20% CO2+60% N2) at 3°C. The effect of high O2 MAP on meat quality varies between different muscles. Jongberg et al. (2014) suggested that chicken thigh is more suitable than breast for storage under high O2 MAP (80% O2 and 20% CO2) at 5°C.

High O2 in MAP contributes to the bright red color of meat which is appealing to consumers (Djenane et al., 2004). However, this packaging system may negatively affect meat qualities due to myoglobin and lipid oxidation and cross-linking/aggregation of myosin by protein oxidation (Kim et al., 2010; Claus and Du, 2013). Therefore, this technique is more frequently use for short time storage of fresh meat.

- **Myoglobin oxidation**

High O2 MAP can maintain the red pigment of oxymyoglobin, but it can also promote pigment oxidation and ultimately accumulation of the brown pigment, metmyoglobin . Lagerstedt et al. (2011) observed that high O2 MAP (80% O2 and 20% CO2) decreased the beef quality parameters including α-tocopherol content and color stability, as well as tenderness, juiciness and meat flavor, which led to premature browning and limited shelf life.

- **Lipid oxidation**

Extensive lipid oxidation generates toxic compounds such as cholesterol oxidation products (COPs). The

changes of COPs in raw and cooked beef packaged with high O2 MAP (80% O2 and 20% CO2) indicated the increased lipid peroxidation rate under high oxygen conditions (Ferioli et al., 2008).

- **Protein oxidation**

Tenderness and juiciness are important quality attributes of fresh meat which are reflective of the water-binding potential and structural integrity of myofibrils and their constituent proteins (Puolanne and Halonen, 2010). Myofibrillar proteins, where the majority of water in meat are imbedded, are particularly susceptible to oxidative processes, such as the destruction of amino acid side chains, peptide scission, and protein cross-linking, which subsequently reduces water-holding capacity (Xiong et al., 2000). Lund et al. (2007b) observed that high O2 MAP (70% O2+30% CO2) induced protein cross-linking and reduced tenderness and juiciness of the porcine longissimus dorsi. Delles et al. (2014) also found that the high O2 MAP (80% O2+20% CO2) system improved red color of salt-marinated boneless pork, promoted hydration of muscle but weakened the water holding ability upon cooking owing to protein oxidation.

### (3) Modified atmosphere packaging containing CO

As discussed above, high O2 MAP meat has attractive red color but this method accelerates the development of meat discoloration (Luño et al., 1998) and oxidative processes (Linares et al., 2007). These disadvantages can be alleviated with the incorporation of CO gas in the packaging, because CO strongly binds to the muscle pigment myoglobin and creates a stable bright red color (Krause et al., 2003). For example, packaging with low CO concentrations together with high CO2 concentrations can improve color and shelf-life of red meat (Krause et al., 2003). However, this has a negative image by consumers because the perceived hazards of CO (Cornforth and Hunt, 2008), although CO does not present a toxic hazard to the consumers for concentrations up to 1% (Sørheim et al., 1997).

Recently, many meat packaging technologies use anaerobic MAP with low levels (about 0.4%) of CO, 20-30% CO2 and the remainder N2 (Cornforth and Hunt, 2008). CO MAP maintained the red color stability of steaks not only during storage but also after opening the packages (Liu et al., 2014). This is related to the phenomena that CO MAP significantly increased metmyoglobin reducing activity, and remained it relatively stable during storage. Some examples of CO MAP for meat and meat products are listed in Table 5.

**Table 5 Some examples of CO MAP for meat and meat products**

| Meat materials | Gas compositions | References |
|---|---|---|
| Loin steaks and ground meat | 1% CO + 20% $CO_2$ + 9% $N_2$ +70% $O_2$; 1% CO + 50% $CO_2$ + 25% $N_2$ + 24% $O_2$ | Luño et al., 2000; Luño et al., 1998 |
| Beef and pork | 0.4% CO + 60% $CO_2$ + 40% $N_2$ | Sørheim et al., 1999 |
| Fresh beef | VP was achieved by pretreatment with 5% CO MAP for 24 h or 100% CO MAP for 1 h | Jayasingh et al., 2001 |
| Beef steak | 0.4% CO + 30% $CO_2$ + 69.6% $N_2$ | Mancini et al., 2009 |
| Spanish Manchega breed lamb meat | 0.7% CO + 30% $CO_2$ + 69.3% $N_2$ | Linares and Vergara, 2012; Linares et al., 2008; Linares et al., 2007 |
| Beef steaks | 0.4% CO + 19.6% $CO_2$ + 80% $N_2$ | Suman et al., 2009; Suman et al., 2010 |
| Manchega breed suckling lamb meat | 0.7% CO + 30% $CO_2$ + 69.3% $N_2$ | Bornez et al., 2010; 2009 |
| Merino fresh lamb meat | 0.4% CO + 30% CO2 + 69.6% Ar | Gutiérrez et al., 2011 |
| Bovine muscles | 0.4% CO + 30% $CO_2$ + 69.6% $N_2$ | Liu et al., 2014 |
| Ground beef | 0.4% CO + 30% $CO_2$ + 69.6% $N_2$ | Rogers et al., 2014 |
| Beef steaks and ground beef | 0.2% CO + 60.0% $CO_2$ + 39.8% $N_2$; 0.2% CO + 99.8% $CO_2$ + oxygen scavengers | Venturini et al., 2014 |

Generally, anaerobic MAP with less than 1% of CO (usually 0.4%) can maintain an attractive color as well as delay microbial spoilage of fresh red meat. Compared with high O2 MAP, CO MAP offers several advantages such as: 1) no premature browning during cooking (John et al., 2004; 2005); 2) limited bone darkening (Mancini et al., 2005); 3) increased tenderness (Lund et al., 2007b); and 4) longer shelf life which allowing continuous action of endogenous tenderizing enzymes (Grobbel et al., 2007).

**(4) Modified atmosphere packaging containing Ar**

Some other gases such as Ar, He, and N2O are permitted for use in meat packaging in the European Union (Directive 95/2/CE; EU, 1995). These gases are generally chemically inert, and can inhibit oxidation reaction even in the presence of O2 with the order xenon (Xe) > krypton (Kr) > argon (Ar) > neon (Ne) > helium (He), whereas N2 has no such ability except for the simple function of displacement of O2 (Spencer, 1994).

Among these gases, Ar is the most studied in food MAP because of its superior chemical inertness and potential to inhibit oxidation and delay microbial growth. For example, gas formulations of 40% O2 +30% CO2 + 30% Ar (Ripoll et al., 2011) and 30% CO2 + 69.6% Ar + 0.4% CO (Gutiérrez et al., 2011) were used to extend the self life of lamb meat, and 30% CO2 + 70% Ar was used to store fresh pork sausages (Claudia and Francisco, 2010), although sometimes Ar MAP was not so efficient in protecting lipid oxidation when compared with N2, and the cost of Ar is much higher (Fraqueza and Barreto, 2009).

### 3.3.3  Packaging materials for MAP

Materials used for meat packaging have been discussed in Section 3.1, which suggested that barrier materials with both limited moisture and gas permeability should be selected to maintain a relatively constant environment within the package during storage (Galić et al., 2011). The permeability of $CO_2$ is 3-5 times higher than that of $O_2$ through most plastic films (Ozdemir and Floros, 2004). Therefore, materials for meat MAP should be carefully designed to achieve the target purpose for different products. For example, polystyrene, polypropylene, and polyethylene are often used in high $O_2$ MAP systems; and a low-barrier polystyrene tray (breathable layer) overwrapped by a barrier film can be used in low $O_2$ MAP (Belcher, 2006). The moisture and gas permeability of multilayer packaging films and trays commonly used in MAP is presented in Table 6, which indicates that suitable film formulations and gas compositions can be designed to optimize the MAP packaging conditions for specific meat and meat products.

**Table 6: Moisture and gas permeability of packaging multilayer films and trays for meat MAP**

| Multilayer films | Permeability | | | References |
| | (cm³/m² d atm) | | (g/m² d) | |
| | Oxygen | Carbon dioxide | Water vapor | |
|---|---|---|---|---|
| PA/PE | 35 | 158 | 15 | Stasiewicz et al., 2012 |
| PA/PE | 30-40 | | 2.5 | Rubio et al., 2007 |
| PA/PE (50/100), thickness of 150 µm, | 7 | 150 | 1.5 | Lauzurica et al., 2005 |
| PA/PE, thickness of 57 µm | 47 | 150-190 | 0.9 | Fernández et al., 2009 |
| PA/PE, thickness of 90 µm | 47 | 150-190 | 7.5 | Fernández et al., 2009 |
| PA/PE, thickness of 95 µm | 50.65 | | 1.64 | Mastromatteo et al., 2011 |
| PA/PE, thickness of 90 µm | 50 | | 2.6 | Speranza et al., 2009 |
| EVA/PVdC, , thickness of 48-62 µm | 25 | | 1 | Fernandes et al., 2014 |
| LDPE/PA/LDPE, thickness of 75 µm | 52.2 | 191 | 2.4 | Petrou et al., 2012 |
| PET-PVdC/PE | 7 | 20 | 4 | Melero et al., 2012 |
| PET-PVdC/PE, thickness of 12 µm/70 µm | <8 | | <5 | Arvanitoyannis et al., 2011 |
| OPA-EVOH/PE | 5 | 1 | 15 | Aksu et al., 2005 |
| OPP/PE-EVOH-PE, thickness of 20µm /50µm | 3 | | | Bingol and Ergun, 2011 |
| PET/PE-EVOH-PE | 1.2 | | | Gunes et al., 2011; Dogu-Baykut and Gunes, 2014 |
| OPA/PE/EVOH/PE/PP | 5 | | | Owczarek-Fendor et al., 2014 |
| PA-EVOH-PA/LDPE-LLDPE, thickness of 40 µm/75 µm | 0.5 | 2 | 4 | Jakobsen and Bertelsen, 2000 |
| PE/PE/PA/EVOH/PA/LLDPE/EVA, thickness of 140 µm | 8.3 | | | Garcia-Esteban et al., 2004 |
| **Multilayer Trays** | | | | |

| | | | |
|---|---|---|---|
| PE/PA | 40-50 | | 5-7 | Sánchez-Escalante et al., 2001; Djenane et al., 2003b |
| PET/EVA-PE (92.31%/7.69%) | 6.48 | | 1.85 | Leygonie et al., 2011 |
| PE/EVOH/PS | 0.99 | 0.55 | 1.69 | Melero et al., 2012 |
| PE/EVOH/PS, thickness of 2 mm | <1 | | | Hempel et al., 2013; Murphy et al., 2013 |
| PE/EVOH/PS | <1 | <4 | | Zakrys-Waliwander et al., 2012 |

OPA: orientated polyamide.

### 3.3.4   Developments of MAP for meat packaging

Generally, MAP is considered as a better technology than VP to maintain meat color during storage (Rao and Sachindra, 2002). In MAP of meat and meat products, one MAP system may have both advantages and disadvantages. For example: fresh meat using low O2 MAP has relatively long storage life before display but displays unfavorable purple color during storage, with potentially for inconsistent blooming after removal from MAP; fresh meat using high O2 MAP has moderate red color stability however oxidation will occur and cooked meat may prematurely brown (McMillin, 2008). Thefrore recently some new techniques have been developed in MAP to improve the safety and quality of the stored meat.

**(1) Synergistic effect of MAP with antioxidant/antimicrobial agents**

Many studies on the application of natural ingredients (antioxidants/antimicrobials) in packaged meat and meat products have demonstrated the additive antioxidation and preservation effects of the ingredients. Among several types of MAP, a combination of high O2 MAP with natural ingredients has been proposed as a way to inhibit the meat oxidation under the oxygenated conditions. For example, surface application of carnosine (50 mM) or ascorbic acid (500 ppm) alone was effective in delaying oxidation of fresh beef steaks under high O2 MAP (70% O2+20% CO2+10% N2) whilst their combination provided the best antioxidative protection (Djenane et al., 2004). In addition, combinations of vitamin C with either rosemary essential oil or taurine could extend the shelf life of the MAP fresh beef steaks by about 10 days (Djenane et al., 2002; 2003a). Petrou et al. (2012) also reported that the combination of chitosan and oregano essential oil under MAP inhibited the microbial spoilage and lipid oxidation, and improved the sensory quality of fresh chicken meat. Details of some recent studies on combining natural ingredients with MAP on stored meat quality are shown in Table 7. Prior to MAP, the natural ingredient treatment can be sprayed on the meat surface in the form of a powder or solution, a dipping treatment, or added directly into meat patties.

Interestingly, the protective effect of antioxidants on meat protein oxidation under MAP may be different from the effect on lipid oxidation or pigment oxidation. For example, Lund et al. (2007a) observed that the addition of antioxidants (rosemary extract and ascorbate/citrate =1:1) did not inhibit or delay oxidation of proteins but protected red meat color and enhanced lipid stability. More studies are needed to explore these effects and their mechanisms.

**(2) Combination of MAP with irradiation**

Recently, the combination of MAP with low dose irradiation (lower than 10 kGy) has also been successfully used to extend the shelf life of various meat products. The combination of gamma irradiation with MAP

decreased nitrosamines in pork sausage (Song et al., 2003), suggesting an improved safety of the meat. Ramamoorthi et al (2009) found that CO-MAP (0.4% CO + 20% $CO_2$ + 79.6% $N_2$) could maintain good color quality of beef, while in combination with irradiation at 1.5 or 2.0 kGy further inhibition of the growth of spoilage microorganisms was observed. In addition, MAP (3% $O_2$+ 50% $CO_2$+ 47% $N_2$) with irradiation (3 kGy) was reported to maintain high product quality and safety of ready-to-cook seasoned ground beef product for 21 d at 4°C storage temperature (Gunes et al., 2011). Turgis et al. (2008) also observed that the shelf life of MAP ground beef was extended to 28 days when essential oils (0.025% Chinese cinnamon, 0.025% Spanish oregano, and 0.075% mustard) in combination with 1.5 kGy irradiation was applied.

**(3) Soluble gas stabilization**

Apart from irradiation treatment, other preservation methods may also be combined with MAP to improve the product quality and safety, such as soluble gas stabilization (SGS) at high $CO_2$ partial pressures (Rosnes et al., 2003). The SGS approach depends on a sufficient amount of $CO_2$ being dissolved into the meat product during 1-3 h treatment prior to high $CO_2$ packaging, which prevents package collapse and improves preservative effect without compromising product quality (Sivertsvik, 2000; Jensen, 2005; Al-Nehlawi et al., 2013). Small-scale SGS treatment has been used for MAP packaging of fish, other seafood and poultry (Al-Nehlawi et al., 2013) and could be a promising method for red meat MAP.

**Table 7: Some recent studies on combining natural ingredients with MAP for meat and meat product packaging**

| Meat with MAP | Natural ingredients | Advantage | References |
|---|---|---|---|
| Beef patties packaged under 70% $O_2$ + 20% $CO_2$ + 10% $N_2$ | Ascorbic acid (500 ppm), taurine (50 mM), carnosine (50 mM), rosemary powder (1000 ppm) and their combinations | Inhibited oxidation of both lipid and myoglobin. | Sánchez-Escalante et al., 2001 |
| Beef muscles packaged under 70% $O_2$ + 20% $CO_2$ + 10% $N_2$ at 1±1°C, 29 d | Sprayed on the surface with vitamin C (500 ppm), taurine (50 mM), rosemary (1000 ppm) and vitamin E (100 ppm), or in combination | Extended the shelf life of fresh beef steaks by about 10 days; delayed myoglobin oxidation and lipid oxidation. | Djenane et al., 2002 |
| Beef steaks packaged under 60% $O_2$ + 40% $CO_2$ | Treated with 1.5% lactic acid alone or antioxidants (0.1% rosemary extract and 0.05% ascorbic acid) | Extended the shelf-life. | Djenane et al., 2003b |
| Fresh beef steaks packaged under 70% $O_2$ + 20% $CO_2$ + 10% $N_2$ | Sprayed with 2% ml/g carnosine (50mM) and carnitine (50mM), L-ascorbic acid (VC, 500ppm) | Provided the antioxidative protection against lipid and color deterioration. | Djenane et al., 2004 |
| Minced beef patties packaged under 100% $N_2$ and 80% $O_2$ + 20% $N_2$ | Rosemary extract and ascorbate/citrate (1:1) | Inhibited oxidation of both lipid and myoglobin; no antioxidant effect was observed in 100% $N_2$ packaging. | Lund et al., 2007a |
| Beef patties packaged under 70% $O_2$ + 30% $CO_2$ | Added 500 ppm phenol-rich white grape extract | Inhibited oxidation of lipid and myoglobin. | Jongberg et al., 2011 |
| Fresh lamb meat packaged under 80% $CO_2$ + 20% $N_2$ | 0.1% thyme essential oil and 0.1% oregano essential oils | Product shelf life was extended by 7-8 days. | Karabagias et al., 2011 |

| Sausages packaged under 5% $O_2$ + 20% $CO_2$ + 75% $N_2$ | Antimicrobial compounds extracted from lemon alkott and thymol, 500ppm | Extended the shelf life of thymol-MAP samples is more than 5 days. | Mastromatteo et al., 2011 |
|---|---|---|---|

**(4) Modeling**

Predicitng the shelf life of MAP meat based on quality and microbial changes is useful to measure and monitor the product quality decline in the meat supply chain. Limbo et al. (2010) developed a predictive model of shelf life of minced beef stored under high O2 MAP (30% CO2 and 70% O2) at different temperatures. It was suggested that different models for MAP could be established based on different products (e.g. fresh or processed meat) and target shelf life (e.g. short time or long time storage) (Hertog et al., 2003).

### 3.3.5    Patents in meat packing using thermoforming films, vacuum packaging and MAP

**(1) Patents on the thermoforming films in meat packaging**

Recently, many patents have been registered on the development of multilayer plastic films as packaging materials with improved gas barrier and mechanical properties. For example, a five-layered, biaxially-oriented, shrinkable tubular film for packaging and wrapping of meat and meat products was developed by Grund et al. (2001). This multilayer film is characterized with superior seal seam strength and high resistance to puncture. Ikemoto and Tsubouchi (2005) developed a heat shrink film with the composites of an aliphatic polyamide resin (40-78%), a xylylene polyamide resin (0-40%), and a polyamide elastomer resin (2-20%), which possess high oxygen barrier properties (oxygen permeability is not more than 150 ml/m2.day.MPa). In contrast, a patent of "Breathable packaging film having enhanced thermoformability" disclosed a packaging film with high oxygen transmission rate of between 2-1000 cm3/100 in2/24 h at 73°C and 0% RH (Lischefski and Nelson, 2008). This film could be used in fresh meat retail packaging as it can permit oxygen to permeate into the package, thereby allowing the meat product to oxygenate which causes a red color desired by consumers. Another oxygen permeable film, a twin lidding film which comprises an inner oxygen permeable film and an outer gas impermeable film, was invented by Roveda and Capitani (2006). This film could be used for high oxygen MAP where meat discoloration is prevented. To improve film heat resistance, a multilayer coextruded film was invented which is comprised of polyester and polyamide layers adhered with a copolymer of polyester and a sulfonic acid or its derivative (Brown, 2005). This film is resistant to temperature of 425 °F (about 218 °C) which is a desired property if the packed meat and meat products will undergo sterilization treatment.

Other patents on thermoforming films for meat packaging include films with anti-fog property (Porter et al., 2003), anti-leak function (Roberge and Fredette, 2009), film with self-weldable outermost layer (Ogiue and Hanai, 2006), multicomponent package with different oxygen barrier properties at each component (Mize, 2005). In addition, single layer polymer films with some enhanced properties have also been disclosed in patents. For example, a film for effectively smoking and/or drying meat products like ham and sausage was developed using a base matrix of an aliphatic polyamide and/or copolyamide and/or terpolyamide with 4.0-50.0% hydrophilic compound (Borodaev et al., 2003). Another film of similar function comprised of a mixture of cross-linked polyvinyl pyrrolidone and polyamide resin was invented by Mori and Arai (2004). This film has moderate water vapour permeability and oxygen impermeability and is also suitable for packaging and smoking of meat products.

**(2) Patents on the VP in meat packaging**

Recent patents on VP in meat packaging are mainly focused on the new packaging methods including high-speed vacuum individual packaging (Haruo and Toshio, 2006) and systems and methods for packaging meat products in low oxygen environment (Hornsby and Trost, 2003), or in high oxygen conditions (Chen, 2007). Another trend is application of some pretreatments before VP to improve the meat quality and safety, such as pre-treatment with bamboo leaf slices or bamboo leaf powder (containg antioxidant and antimicrobial compounds) (Lee, 2005), combining gaseous CO pretreatment with VP for half-finished or raw meat products (Cherevko et al., 2005), and infusing fresh meat product with solutions containing sodium nitrate (Summerfield et al., 2011).

**(3) Patents on the MAP in meat packaging**

Similar to those for VP, some patents on MAP for meat also utilize pretreatments of natural plant extracts. For instance, Sandusky et al. (2001) invented a method of extending the fresh meat colour life by applying Labiatae plant extracts on the meat prior to high $O_2$ MAP (> 40% $O_2$). A natural plant component containing a sufficient amount of nitrites was also used in low $O_2$ MAP to improve the color of the fresh meat product (Baublits and Sawyer, 2010). Optimization of the gas composition, such as using high $O_2$ content, low CO, adequate quantity of $CO_2$ and some noble gases, has been the topic of patents in meat MAP. Rasanayagam and Sundaram, (2012) developed a CO-MAP method declared in the patent "Plasma generation of CO for modified atmosphere packaging" which applied an electric field to generate a gas comprising of $CO_2$ and CO. The fresh appearance of meat is maintained for a longer time by storing them in a container with this mixed gas. More recently, a very high Ar concentration MAP, using 40-80 vol.% Ar, 20-40 vol.% $CO_2$, with the remainder as $N_2$, was invented by Laimer (2011) to pack fresh meat or sausages. This technique exhibited significantly improved meat quality (e.g. taste, flavor, color, freshness, and stability) and extended storage time.

It was noted that some new patents on thermoforming films of VP and MAP meat packaging combine these methods with active packaging, such as adding a carbon dioxide scavenger in the VP film (Ebner and Stockley, 2006) and a myoglobin blooming agent (e.g. nitric oxide donating compounds, nitrogen heterocycles or sulfur monoxide donating compounds) in thermoforming films to improve colour quality of the meat (Siegel and Nelson, 2010).

## 4.0    Recent innovations in meat packaging

The basic functions of traditional packaging have been classified as protecting the product against the deteriorative effects of the external environment, communicating with the consumer as a marketing tool, providing the consumer with greater ease of use and time-saving convenience, and containing products of various sizes and shapes (Robertson, 1993). However, innovative packaging with enhanced functions is constantly sought in response to the consumer demands for minimally processed foods with fewer preservatives, increased regulatory requirements, market globalization, concern for food safety, and the threat of food bioterrorism (Yam, Takhistov, & Miltz, 2005). Active packaging, intelligent packaging, edible coatings/films and biodegradable packaging, and nanotechnology are the major recent innovations in the food packaging industry that have shown promising advanced properties in extending shelf life, improving food safety and quality, and protecting our natural environment.

## 4.1    Active packaging in meat packaging

Active packaging is an innovative packaging system/technology that allows the product and its environment to interact to extend the shelf life and/or to ensure food microbial safety, while maintaining the quality of the packed food (Ahvenainen, 2003). In the United States, the term "active packaging" generally describes any packaging system that protects food from contamination or degradation by creating a barrier to outside conditions while interacting with the internal environment to control the atmosphere within the package (Ettinger, 2002). Based on the European Union Guidance to the Commission Regulation No 450/2009 (EU, 2009), active packaging is a type of food packaging with an extra function, in addition to that of providing a protective barrier against external influence. Active packaging is intended to influence the packed food. The packaging absorbs food-related chemicals from the food or the environment within the packaging surrounding the food; or it releases substances into the food or the environment surrounding the food such as preservatives, antioxidants, and flavourings. The "releasing active materials and articles" are those designed to deliberately incorporate components that would release substances into or onto the packaged food or the environment surrounding the food; and "released active substances" are those intended to be released from releasing active materials and articles into or onto the packaged food or the environment surrounding the food and fulfilling a purpose in the food (EU, 2009).

**Table 8. Purpose, method, type and function of active packaging**

| | Function of active packaging |
|---|---|
| Method | Add active compounds (gas scavengers, release agents, antimicrobial and antioxidant agents) |
| Purpose | Retain food quality, extend shelf-life, and ensure food safety |
| Types | Antimicrobial releasing, moisture absorbing, $O_2$ scavenging, $CO_2$ scavenging/releasing, ethylene scavenging/releasing |
| Advantage | Extend shelf-life, ensure food safety |
| Disadvantage | Potential migration of active compounds into food that may lead food quality and safety concern |

Table 8 is the summary of the purpose, method, type and function of active packaging. Comprehensive reviews on the utilization of active packaging system for fresh meat and meat based products have been provided by Kerry et al. (2006) and Coma (2008), and more recently by Sun and Holley (2012), Arvanitoyannis and Stratakos (2012), and Realini and Marcos (2014). Most important active packaging

systems applied to meat and meat products are antioxidant and antimicrobial packaging, carbon dioxide emitters, and oxygen scavengers, which are discussed in great detail later in this section.

An overview of the important active packaging systems for meat and meat products will now be presented, giving examples of their commercial applications, and providing research trends and innovations in active packaging for meat and meat products.

### 4.1.1 Antimicrobial active packaging

Antimicrobial active packaging is one of the most important concepts in active packaging because meat provides excellent nutrients for the growth of microorganism. Spoilage microorganisms including bacteria, yeast and molds, and pathogenic micrograms, specifically Salmonella spp., S. aureus, L. monocytogenes, C. perfringens, C. botulinum, and E. coli O157:H7 are the major concerns leading to quality deterioration and food safety issues in meat (Jayasena and Jo, 2013). The aims of using antimicrobial active packaging are to extend shelf-life and to ensure food safety of meat and meat products.

According to Cooksey (2001) and Coma (2008), there are three basic categories of antimicrobial packaging: 1) incorporation of an antimicrobial substance into a sachet/pad connected to the package from which the volatile bioactive substance is released during further storage; 2) direct incorporation of the antimicrobial agent into the packaging film; and 3) coating of packaging with a matrix that acts as a carrier for antimicrobial agents so that the agents can be released onto the surface of food through evaporation in the headspace (volatile substances) or migrate into the food (non-volatile additives) through diffusion.

In addition, based on the EU Guidance to the Commission Regulation No 450/2009 (EU, 2009), there are 3 major categories of antimicrobial active packaging depending on the function of antimicrobial substances in the food contact materials:

- Process antimicrobials keep the material or preparations to be processed into final food contact materials (e.g. pre-polymer solutions) free from microbial contamination during the production, storage or handling process;

- They are used as components in the manufacture of food contact materials but not intended to be present in the food contact material itself.

- As no antimicrobial function is exerted on the final food contact material, the food contact material could not be regarded as treated article.

- Surface antimicrobials keep the surface of the food contact material free from microbial contamination (e.g. used on inner surface of fridges, cutting boards, gaskets, conveyer belts, storage containers). However, the antimicrobials are not intended to be transferred to food or its environment and it does not have any technological effect on the food.

- Preservatives have a technological effect on the food. They are defined as substances which prolong the shelf-life of foods by protecting them against deterioration caused by microorganisms and/or which protect against growth of pathogenic microorganisms. Their function is to prolong self-life by protecting food against deterioration caused by microorganisms and/or to protect against growth of pathogenic micro-organisms.

A packaging application in which a preservative is intentionally incorporated to be released into the food is considered as an active material or article. The antimicrobial is then the released active substance having a technological function on the food. It can be used if it is an authorised food preservative.

Appendinia and Hotchkiss (2002) also stated that antimicrobial active packaging can take several forms, including:

- Addition of sachets or pads containing volatile antimicrobial agents into packages.

- Incorporation of volatile and non-volatile antimicrobial agents directly into polymers.

- Coating or adsorbing antimicrobials onto polymer surfaces.

- Immobilization of antimicrobials to polymers by ionic or covalent linkages.

- Use of polymers that are inherently antimicrobial.

A large number of antimicrobial agents, including ethanol, carbon dioxide, silver ions, chlorine dioxide, antibiotics, bacteriocins, organic acids, essential oils, and spices have been tested for the purpose of inhibiting the growth of microorganisms in foods (Suppakul et al., 2003; Zhao et al., 2013). Arvanitoyannis and Stratakos (2012) summarized the previous studies on the effect of antimicrobial active packaging on the physical and sensory properties of some meat and meat products, including beef steaks and cooked whole or sliced hams. Among these antimicrobial active packaging studies, plant extract (rosemary extract), peptides, and nisin were used as antimicrobial agents. Recently, essential oils have attracted great attention as natural antimicrobial agents in meat and meat products. Jayasena and Jo (2013) reported the components of major essential oils, discussed their mode of action, and summarized the studies testing the antimicrobial activity of essential oils or their components when added into meat and meat products. It was concluded that phenolic compounds, such as carvacrol, eugenol, and thymol, are the main components responsible for the antimicrobial activity of essential oils to increase the permeability of cell membranes and leading to loss of cellular constituents. However, the intense aroma of essential oils has partially limited their application, which can be overcome through encapsulation of essential oils into nanoemulsions.

Several companies have commercialized various antimicrobial packaging that can be applied for meat and meat product packages (Table 9).

**Table 9. Examples of commercially available antimicrobial active packaging**

| Product and manufacturer | Active compounds | Description |
|---|---|---|
| Aglon™, Agion Technologies | Silver zeolite | Films, paperboard cartons, wraps |
| Bactiblock®, NanoBioMaters, Spain | Silver | Masterbatch |
| Bioka, Bioka Ltd., Finland | Glucose oxidase | Sachets |
| Biomaster®, Addmaster Ltd., UK | Silver | Masterbatch |
| Biomaster®, Linpac Packaging Ltd., USA | Silver | Trays and films |
| d$_2$p®, Symphony Environmental Ltd., UK | Silver | Trays and films |
| Ethicap™, Freund, Japan | Ethanol vapor emitting | Sachets |
| Food-touch®, Microbeguard Co., USA | | Liner/cover, interleavers, papers, wraps |
| IonPure®, Solid Spot LLC, USA | Silver | Masterbatch |
| Irgaguard®, BASF, USA | Silver | Masterbatch |
| Microban, Microban Prod., UK | Tricolsan | Plastic packaging |

| Microgarde™ and Microsphere™, Bernard Technologies, USA | Chlorine dioxide | Sachets, films, wraps |
|---|---|---|
| Novaron®, Toagosei, Japan | Silver | Films, paperboard cartons, wraps |
| Negamold Oitech, Nippon Kayalan, Japan | Ethanol vapor emitting | Sachets |
| Sanic Films, Nanopack Technology & Packaging, Spain | Mineral components such as essential trace elements | Interleavers, films |
| Sanico®, Laboratories STANDA | Natamycine | Antifungal coating |
| Surfacine®, Surfacine Development Co. LLC., USA | Silver | Masterbatch |
| Uvasy™, Grapetek, South Africa | Sulfur dioxide | Laminated sheets and pads |
| WasaOuro, Lintec Corp., Japan | Ally lisothiocy ante | Sheets |
| Wasaouro®, Mitsubishi-Kagaku Foods Co., Japan | Allyl isothiocyanate | Antibacterial and antifungal sheets, labels, and films |
| Wasapower™, Sekisui Plastics Co., Ltd., Japan | Wasabi extract encapsulated in cyclodextrin | Coated PEF and tablets |
| Zeomic™, Sinanen Co., Ltd., Japan | Silver | Films, paperboard cartons, wraps |

Source: Modified from Coma (2008), Realini and Marcos (2014), and Sung et al. (2013).

For the effective application of antimicrobial active packaging in meat and meat products, the selection of an effective delivery method and antimicrobial substance, and minimal impact on the sensory properties of packaged product are the key points that should be considered. For example, while essential oils show promise against microorganisms, the negative organoleptic effects due to their intense aroma partially limits their application. Novel technologies such as encapsulation of essential oils into nanoemulsions and the use of essential oils as part of hurdle technology (combined processes with MAP, nisin, EDTA, and lysozyme) to improve the microbial stability and the sensory quality of meat and meat products are being used in the meat industry. Traditional methods of adding essential oils directly into meat batter during manufacturing of meat products are also used.

Realini and Marcos (2014) stated that although extensive research has been carried out on the development of antimicrobial packaging solutions, this type of active packaging has had limited commercial success. The main constraints for the commercialization of active antimicrobial packaging systems are mainly regulatory and also technical limitations that still need to be solved. To successfully implement antimicrobial packaging solutions in the market, a multidisciplinary approach involving researchers from different disciplines (food, microbiology, and material science) working together with the packaging industry is necessary.

### 4.1.2 Antioxidant active packaging (oxygen-scavenging packaging)

High levels of oxygen present in meat packaging can facilitate microbial growth, lipid oxidation, development of off flavours and off odours, colour changes and nutritional losses. Lipid oxidation not only results in the development of off-flavours (rancidity), but also the potential formation of toxic aldehydes and the loss of nutritional quality because of polyunsaturated fatty acid (PUFA) degradation (Gomez-Estaca et al., 2014). Therefore, control of oxygen levels in meat packaging is important to limit the rate of such deteriorative and spoilage reactions. Antioxidant active packaging can be used as a means of improving product quality and extending shelf life of meat and meat product through controlling the level of oxygen.

Gomez-Estaca et al. (2014) gave a very comprehensive review of the advances in antioxidant active

packaging sytems and classified them into two approaches: 1) independent antioxidant devices, and 2) antioxidant packaging materials.

*Independent antioxidant devices* - An independent device such as a sachet, pad or label containing oxygen scavengers that is separated from the food product and is added to a conventional 'passive' package. Iron and ferrous oxide fine powders are the most common oxygen scavengers, although ascorbic acid, sulphites, catechol, ligands, and enzymes such as glucose oxidase are also utilized (Brody et al., 2008). To prevent scavengers from acting prematurely, specialized mechanisms can trigger the scavenging reaction. For example, iron-based scavengers require the presence of humid conditions to activate oxygen removal (Lopez Rubio et al., 2004). Brody et al. (2001, 2008), Rooney (2005) and Suppakul et al., (2003) have provided extensive reviews about the uses and applications of oxygen scavenging packages. Table 10 shows some of the commercially available O2-scavengers.

*Antioxidant packaging materials* – In this approach, the active agent is incorporated in the walls of the package films or containers exerting its action by absorbing undesirable compounds from the headspace or by releasing antioxidant compounds to the food or the headspace surrounding it. The manufacturing procedure is selected taking into consideration of the type of polymer and the characteristics of the antioxidant agents, especially heat resistance and mechanism of action. If the antioxidant activity of the material is based on a migration process into the food, the substances released should be a permitted food additives and comply with the appropriate regulations in terms of it maximum allowable concentration. Technologically, the agent (or the reactive substances which produce the agent) is intimately mixed with the polymer, either 1) by dissolving both into an appropriate solvent followed by application of the solution to a substrate using coating technology, 2) by polymer melting and incorporation and mixing of the agent in the melt using extrusion technologies, or 3) immobilization of the antioxidant on the film surface (Gomez-Estaca et al., 2014). Gomez-Estaca et al. (2014) has previously given very detailed descriptions about these different approaches.

**Table 10: Commercially available O2-scavengers packaging materials for food applications**

| Product and manufacturer | Description |
| --- | --- |
| ActiTUF™, M&G Finanziaria s.r.l., Alessandria, Italy | Barrier resins |
| Aegis HFX Resin and OXCE Resin, Honeywell International Inc., USA | Barrier nylon resin |
| Ageless G, Mitsubishi Gas Chemical, Japan | Sachets |
| Amosorb®, Amosorb SolO2, ColorMatrix Group Inc., USA | Resin |
| ATCO®, Laboratories STANDA | Label |
| Bioka Oxygen Absorber Sachets, Film Laminate, Bioka Ltd., Kantvik, Finland | Sachets |
| Celox™, Grace Darex Packaging Technologies, USA | Closure sealant, masterbatch |
| Cryovac®, OS Film Sealed Air Corporation, USA | Film |
| Desi Pak®, Sorb-It®, Tri-Sorb®, Getter Pak®, 2-in-1 Pak®, Süd-Chemie AG, Munich, Germany | Sorb, pak, |
| Enzyme-based, Bioka Ltd., Kantvik, Finland | Film |
| Label Cryovac®, OS2000 Sealed Air Corporation, USA | Film |
| Verifrais, SARL Codimer, France | Sachets |
| FreshPax®, Multisorb Technolgoies, Inc., USA | Sachets |
| O2S®, Bericap GmbH und Co. KG, Germany | Caps, closures |
| O-Buster®, Hsaio Sung Non-Oxygen Chemical Co., Ltd., Taiwan | Sachets |
| OMAC®, Mitsubishi Gas Chemical Inc., Japan | Film suitable for high temperature |
| Oxbar®, Constar International Inc., Plymouth, USA | Resin |

| | |
|---|---|
| OxyGuard®, Clariant Ltd., Switzerland | Sachets |
| OxyCatch®, Kyodo Printing Co., Ltd., Japan | Sachets |
| OxyRx®, Mullinix Packages Inc., USA | Container suitable for high temperature |
| Shelfplus® $O_2$, Albis Plastic GmbH | Masterbatch |
| Tri Sorb, Tri Shield, Tri Sorb EVA, Tri Shield EVA blue, EVA Tri-Seal, Tekni-Plex, Belgium | Sorb, shield, tri-seal |
| ATOX, Artibal SA, Spain | Film coating with antioxidant |

Source: Modified from Kerry et al. (2006) and Pereira De Abreu et al. (2012).

Sanches-Silva et al. (2014) reviewed the natural antioxidants already applied in active packaging, and provided a very comprehensive list of the films (synthetic, biodegradable and edible films) incorporated/mixed with natural antioxidants. The most recent contribution in antioxidant active packaging is the use of natural antioxidants, including tocopherols, varvacrol, essential oils, and plant and fruit extracts (eg. green tea extracts, grapefruit seed extracts). Barbosa-Pereira et al. (2014) also stated that the current trend in antioxidant active packaging is to reduce the use of synthetic additives in packaging and their substitution by natural antioxidants, particularly tocopherol. Plant extracts and essential oils from herbs such as rosemary, oregano, and tea, are of great interest as natural antioxidants. In many cases these extracts and oils can also offer health benefits to the consumer.

Realini and Marcos (2014) presented a very good remark about antioxidant active packaging saying,

*"It is a promising technique for extending shelf life of meat and meat products and even though significant progress has been made through research and innovation, it is a developing technology, and current research is in its early stages".*

Tian et al. (2013) highlighted challenges and key areas for future research in antioxidant active packaging, including a rigorous evaluation of the retained antioxidant activity and stability after being added into a packaging material, and a particular attention to the characteristics of each food product to select the most suitable active agents and application approaches. Also, the migration of active substances from packaging materials should be considered. Lee (2014) pointed out that the maximum effectiveness of antioxidant packaging systems can be achieved by matching the antioxidant release kinetics with the lipid oxidation kinetics. Mathematical models of diffusion can be a valuable tool to predict the release profile of antioxidants into food systems (Piringer, 2000). Further research should be conducted to control the diffusion rate of the bioactive compounds in packaging meat and meat products during storage for maximum effectiveness.

### 4.1.3 Carbon dioxide emitting/generating packaging

$CO_2$ has inhibitory activity against a range of aerobic bacteria and fungi, as well as direct antimicrobial effect, resulting in an increased lag phase and generation time during the logarithmic phase of microbial growth. Therefore, a carbon dioxide generating system can be viewed as a technique complimentary to oxygen scavenging (Suppakul et al., 2003). For most applications in meat and poultry preservation, high $CO_2$ levels (10–80%) are desirable because these high levels inhibit surface microbial growth; thereby extending shelf-life (Vermeiren et al., 1999, Kerry et al., 2006). The inhibitory action of $CO_2$ has differential effects on different microorganisms. Whereas aerobic bacteria such as Pseudomonas can be inhibited by moderate to high levels of $CO_2$ (10–20%), lactic acid bacteria can be stimulated by $CO_2$. Furthermore, pathogens such as C. perfringens, C. botulinum and L. monocytogenes are minimally affected by $CO_2$ levels lower than 50%. However, there is concern that by inhibiting spoilage microorganisms, a food

product may be made to appear edible while containing a high quantity of pathogens that have multiplied due to a lack of indigenous competition (Yingyuad et al., 2006). Moreover, a higher production of C. botulinum toxin with high concentration of CO2 has been reported even though a decrease in the growth rate was observed (Lovenklev et al., 2004).

Commercial examples of carbon dioxide emitters applied in muscle foods incorporated in the form of sachets and absorbent pads have been previously presented and discussed (Coma, 2008; Kerry et al., 2006; Realini and Marcos, 2014). Carbon dioxide emitters allow the reduction of the packaging headspace by reducing the gas to product volume ratio compared to optimal modified atmosphere packaging (MAP). Carbon dioxide absorbers (sachets), consisting of either calcium hydroxide and sodium hydroxide, or potassium hydroxide, calcium oxide and silica gel, may be used to remove excess carbon dioxide during storage in order to prevent bursting of the package, an approach that has been used in packs of dehydrated poultry products and beef jerky (Ahvenainen, 2003). This type of active packaging is frequently associated with MAP systems in order to balance out CO2 losses due to dissolution into the meat and permeation through the packaging material (Coma, 2008).

Table 11 presents some of the commercial CO2 emitters and generators. For example, CO2 emitting VerifraisTM (Codimer, France) or the CO2 generators/O2 scavengers Ageless G (Mitsubishi Gas Chemical Co., Japan) and FreshPax M (Multisorb Technologies Inc., USA) have been used to extend the shelf life of fresh meat. Such emitting/scavenging systems are based on either ferrous carbonate or a mixture of ascorbic acid and sodium bicarbonate. CO2®FreshPads (CO2 Technologies, USA) are used for meat, poultry, and seafood packaging. Drip losses from muscle foods are absorbed into pads and react with citric acid and sodium bicarbonate present in the pad resulting in the generation of CO2 (Kerry et al., 2006). A more evolved version of CO2 generators, UltraZap® XtendaPak pads, has been launched by Paper Pak Industries (CA, USA). It is designed as an absorbent pad for fresh meat, poultry and fish that has a double antimicrobial effect due to the incorporation of a CO2 emitter and an antimicrobial substance (Paper Pak Industries, 2014). A CO2 emitter, consisting of a coated expanded polystyrene box with a CO2 emitter, Vartdal Plastindustri AS (Norway) is also available for meat packaging (Vartdal Plastindustri, 2009). Reported system advantages are prolonged shelf life, reduced transport volume, less environmental impact and no bulging or vacuum effect.

A recent study on the use of active packaging systemsto control the microbial quality of ready-to-eat meat products was conducted by Chen and Brody (2013). Cooked ham samples were packed into three antimicrobial packaging systems including a nylon/EVOH/polyethylene oxygen barrier bag and an antimicrobial film (CSP Technologies, three-phase Activ-Polymer® technology, US Pattent 7,005,459) with the capacity of generating CO2 or generating allyl isothiocyanate or scavenging O2. Packaging structures with O2 scavengers or CO2 generators proved to control bacterial populations, particularly Listeria, while the allyl isothiocyanate generator only had limited antimicrobial effects. Realini and Marcos (2014) stated that the growth and development of the CO2 emitter market is likely to progress towards the development of films that incorporate the carbon dioxide emitter functionality (Day, 2008). Although research into this concept is still in its early stages, there are some commercial applications as stated above.

**Table 11: Some commercial CO2 emitters**

| Product and manufacturer | Description |
| --- | --- |
| Ageless G, Mitsubishi Gas Chemical, Japan | Sachets |
| $CO_2$® Fresh Pads, $CO_2$ Technologies, USA | Pads |
| Freshpax, Multisorb Technologies, USA | Sachets |
| Freshlock, Multisorb Technologies, USA | Sachets |
| Standa, France | Gel into sachets in contact with the food |
| Superfresh, Vartdal Plastindustri AS | Box system with $CO_2$ emitter |
| UltraZap® Xtenda Pak pads, Paper Pak Industries, Canada | $CO_2$ emitter and antimicrobial pad |
| Verifraise package, SARL Codimer, France | Sachets containing sodium bicarbonate/ascorbate |

Source: Modified from Coma (2008), Realini and Marcos (2014), and Kerry et al. (2006).

### 4.1.4 Recent patents of active packaging for meat and meat products

Active packaging technology has been heavily patented. In respect to active packaging for meat and meat products, the technology inventions have mainly focussed on antioxidant and antimicrobial concepts for preventing lipid oxidation and controlling the growth of spoilage and pathogenic microorganisms. Some of the recent inventions (2001-2014) in active packaging for meat and meat products are described here.

**1). Antimicrobial active packaging for meat and meat products**

Duncan and Robert (2001) invented a meat product packaging comprising a sheet material substrate having antimicrobial agent of essential oils (linalool, tuφineol, eugenol, thymol, citral or carvacrol) or an ester of 4-hydroxybenzoic acid. The meat product packaging can be used to package products prior to delivery to shops and other food outlets, or can be used for domestic use. Evans et al. (2003) designed a packaging system to include acid to control meat for maintaining meat safety and quality.

Zhou et al. (2012) designed an active packaging film for chilled meat by employing polyvinyl acetate (PVA) and polylactic acid (PLA) as film-forming materials and sustained-release microcapsules containing natural antimicrobial agent. The antimicrobial agent is slowly released from the microcapsules, migrates in the film and finally reaches the surface of the chilled meat to achieve antimicrobial and fresh-keeping effects. Chao (2013) invented a nano-preservation method through vacuum packaging, putting one nano-bioactive detoxification antistaling agent in packaged fresh meat for chilled fresh meat to prolong shelf-life, improve taste, and enhance nutrients of the chilled fresh meat.

Ortolani et al. (2013) developed a packaging comprising a first layer of paper coupled to a second layer of polyethylene (or from biodegradable end compostable plastic material), and an optional third metallic layer. This system is characterized by the fact that on the surface of the second layer facing towards or in contact with the food, a natural extract or an essential oil or at least one active molecule (isolated from Rosmarinus officinalis or Citrus limon or Vitis vinifera or their mixture) is applied. The material is particularly suitable for packaging meat or fish to inhibit the development of potential health risk compounds of biogenic amines.

Guarda et al. (2014) also invented a three layer coextruded system to for a film incorporating natural antimicrobial agents in a polymeric structure. This film was designed for packages to increase the shelf life of chilled or refrigerated meat. Versteylen and Riehle (2014) designed an absorbent food pad comprising of a body having an architecture of a top layer for contact with a food product and a bottom absorbent pad layer for uptake of "drip". The active agent in this system consisted of an antimicrobial, a

CO2 generation system, an oxygen scavenger, or any combination of these. Burnett et al. (2014) invented a method of using an antimicrobial composition on ready-to-eat meat where the antimicrobial composition is applied directly to the meat product, and then the meat product is packaged and sealed.

### 2). Antioxidant active packaging for meat and meat products

Ebner et al. (2006) developed a sachet of oxygen scavenger compounds derived from isophthalic or terephthalic acid monomers and derivatives. The sachet can protect dried meat, ham, sausage, pork or beef jerky from oxidation. Siegel and Cascao-Pereira (2007) and Pockat et al. (2014) designed heat shrinkable and oxygen barrier packaging films that have a myoglobin blooming agent to provide, promote, enhance or maintain a desirable coloration on the surface of myoglobin-containing meat products. Cascao-Pereira et al. (2008) patented a technology for making co-extruded multilayer film, which incorporated an antioxidant-containing layer and an external barrier layer impermeable to the antioxidant preventing it from migrating outward from the bag. This coextruded multilayer film increases the retention of volatile antioxidants such as essential oils, making it more effective for improving and extending the storage life of meat susceptible to oxidation and oxidative rancidity.

Holst et al. (2012) invented a package for treated fresh meat products comprising of a fresh meat product, a solution, and a low to no oxygen packaging. The solution includes a source of sodium nitrite or sodium nitrate that is infused into the fresh meat product to create a treated fresh meat product. Slinde and Egelandsdal (2014) provided methods for treating uncooked meat to improve its colour stability and/or for reducing the onset of rancidity. The method involved contacting the uncooked meat with a fomulation consisting of succinate and one or more of glutamate, malate, citrate, isocitrate, aconitate and pyruvate as active components.

### 3). Active packaging for achieving desirable red meat colour

Several inventions for preserving red colour of fresh meat have been patented, including 1) a method comprising a myoglobin blooming agent for promoting or preserving the desirable appearance of meat through a food contact layer of the packaging films incorporating a myoglobin blooming agent (Siegel and Nelson, 2012a), 2) a film including an effective amount of a nitrogen-containing compound contained within or applied to one side of the film and designed to contact the meat held within a food packaging container. This system improves the visual appearance of fresh meat (Siegel and Nelson, 2012b), 3) a method of distributing or commercialising myoglobin-containing fresh meat through packaging the retail cuts into a plurality of articles wherein each article consists of a polymeric oxygen barrier film having a transparent portion in contact with at least a portion of the fresh meat product, and transporting the packaged article to a retail outlet, wherein the packaged article is adapted for retail display and sale without removing the polymeric film and where the fresh meat product has a desirable red color (Siegel et al., 2013), and 4) food packaging systems and food packaging methods comprising a myoglobin blooming agent and synergist that promote or preserve the desirable appearance of meat, in which the food contact layer of the packaging systems may comprise a myoglobin blooming agent and a synergist (Siegel et al., 2014).

## 4.2    Intelligent packaging in meat industry

In Europe, the legal definition of *"intelligent food contact materials and articles"* is *"materials and articles that monitor the condition of packaged food or the environment surrounding the food"* (The Commission of the European Communities, 2004). In contrast, an academic definition for intelligent packaging was proposed by Yam, Takhistov, & Miltz (2005) which is *"a packaging system that is capable of carrying out*

*intelligent functions (such as detecting, sensing, recording, tracing, communicating, and applying scientific logic) to facilitate decision making to extend shelf life, enhance safety, improve quality, provide information, and warn about possible problems".*

Compared with "active" packaging that positively changes the condition of the package to improve food safety and quality to extend shelf life (Vermeiren, Devlieghere, van Beest, de Kruijf, Debevere, 1999), an "intelligent" package is able to track the product, sense the internal/external environment of the package, and communicate with the human (eg. consumer). Therefore, an intelligent packaging is one that monitor the quality/safety condition of a food product and can provide early warning to the consumer or food manufacturer, whereas an active packaging is one that takes some actions (e.g. release of an antimicrobial or antioxidant) to protect the food product. It is noted that the terms intelligent packaging and active packaging are not mutually exclusive as some packaging systems may be classified as both. Although intelligent packaging was, a decade ago, not a commercially viable concept due to package devices and computer networks being expensive and quite limited, the more powerful and affordable information technology now available has created a favorable environment for this technology to flourish (Yam, Takhistov, & Miltz, 2005).

**Table 12 Examples of smart devices used in intelligent packaging and their principle of operation (Modified from Hurme, Sipiläinen-Malm, Ahvenainen, & Nielsen, 2002)**

| Smart devices | Principle/reagents | Information given | Application |
|---|---|---|---|
| Barcodes | Symbology | Product and manufacturer information | Product identification, facilitating inventory control, stock reordering, and checkout |
| Radio frequency identification tags | Radio waves | Product and manufacturer information | Product identification, supply chain management, asset tracking, security control |
| Time–temperature indicators | Mechanical, chemical, enzymatic, microbiological | Storage conditions | Foods stored under chilled and frozen conditions |
| Gas indicators | Redox dyes, pH dyes, enzymes | Storage conditions, package leak | Foods stored in packages with required gas composition |
| Freshness indicators (e.g. Microbial growth) | pH dyes; Dyes reacting with (non-) volatile metabolites | Microbial quality of food (i.e. spoilage) | Perishable foods such as meat, fish and poultry |
| Pathogen indicators | Various chemical and immunochemical methods reacting with toxins | Specific pathogenic bacteria such as *E. coli* O157 | Perishable foods such as meat, fish and poultry |

An intelligent packaging system contains smart devices which are small, inexpensive labels or tags that are capable of acquiring, storing, and transferring information about the functions and properties of the packaged food. The most commonly used smart devices in intelligent packaging of meat and meat products are summarised in Table 12.

### 4.2.1   Barcode

A barcode is an optical machine-readable symbol relating to the object to which it is attached. The first commercialized barcode was the UPC (Universal Product Code) introduced in the 1970s that has now become ubiquitous in grocery stores for facilitating inventory control, stock reordering, and checkout

(Manthou and Vlachopoulou 2001). The UPC barcode is a linear symbology consisting of a pattern of bars and spaces to represent 12 digits of data containing limited information such as manufacturer identification number and item number (Yam, Takhistov, & Miltz, 2005) (Figure 1). To address the growing demand for encoding more data in a smaller space, new families of barcode symbologies such as Reduced Space Symbology (RSS), two-dimensional (e.g. PDF 417, Aztec code), Composite Symbology (combining a 2-D barcode such as PDF 417 with a linear barcode such as UPC) and GS1 DataBar Family (Uniform Code Council, 2014) (Figure 2) have been introduced. Information including food packing date, batch/lot number, package weight, nutritional information, cooking instructions and the Web site address of food manufacturer can ben encoded in the barcodes and they are even readable by smartphones; providing great convenience for both retailers and consumers. Barcodes are also good devices to identify the origin of food products and are widely used in meat and meat product packaging. In Australia, almost all meat and meat products in the retail market are sold with a barcode.

| Examples | Name |
|---|---|
|  | UCP barcode |
|  | RSS barcode |
|  | PDF 417 barcode |
|  | Aztec code |
|  | GS1 barcode |

Figure 2. Some examples of barcodes

## 4.2.2 Radio frequency identification (RFID) tags

RFID technology is a form of electronic information-based intelligent packaging. Compared with barcodes, the RFID tag is a more advanced data carrier for product identification with several unique characteristics, such as significantly larger data storage capacity (up to 1 MB for high-end RFID tags), non-contact, non-line-of-sight ability in gathering real-time data, and can penetrate non-metallic materials for rapid and automatic multiple product identification (Mennecke & Townsend, 2005). Nevertheless, the RFID tag is not considered as a replacement for the barcode, mainly because of its relatively higher cost and need for a more powerful electronic information network. It is anticipated that both RFID and barcode data carriers will continue to be used either alone or in combination, depending on the situation (Yam, Takhistov, & Miltz, 2005).
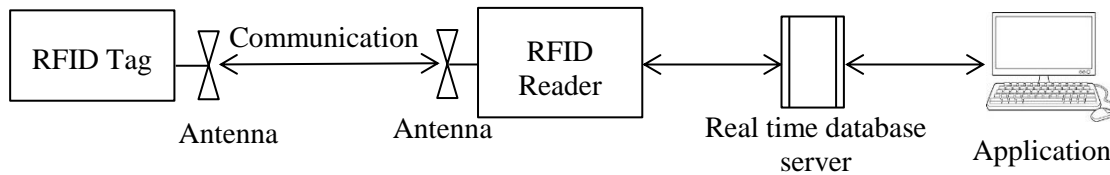
Figure 3. A basic RFID system

In a basic RFID system, an RFID tag contains a tiny transponder and antenna that have a unique number or alphanumerical sequence; a reader emits radio waves to capture data from the RFID tag and the data is then passed through a real time database server onto a host computer (that may further connect to a local network or the Internet) for analysis and decision making (Want 2004) (Figure 3). The RFID tags may be classified into passive and active tags. The passive tags have no battery and are powered by the energy supplied by the reader whereas the active ones have their own battery for powering the microchip's circuitry and broadcasting signals to the reader. The more expensive active tags have a reading range of more than 50 meters, while the less expensive passive tags have a reading range of up to 5 meters. The actual reading range depends on factors such as the frequency of operation, the power of the reader, and the possible interference from metal objects (Yam, Takhistov, & Miltz, 2005). Low frequency (~125 kHz) tags are cheaper, use less power and are better able to penetrate non-metallic objects. These tags are most appropriate for use with meat products, particularly where the tags might be obscured by the meat itself and are ideal for close-range scanning of objects with high water content (Kerry, O'Grady, & Hogan, 2006).

Although RFID technology has been available for approximately 50 years, its broad application to meat packaging has only begun recently (Kerry, O'Grady, & Hogan, 2006). The costs of RFID are decreasing rapidly, as major companies such as Wal-Mart, 7-Eleven and Marks & Spencers adopt the technology. At the time of this writing, a passive tag costs between 30¢ and $1 depending on the quantity ordered (Anonymous 2014a). For the technology to be truly competitive, it was estimated that tags must cost less than 5¢ or even 1¢ (Want, 2004; Mennecke & Townsend, 2005). Because some tags can be reprogramed thousands of times, it is now practical that the cost of each time that the tag is read and written is less than 1¢ (Anonymous 2014a).

The RFID tags offer several potential benefits to the meat production, distribution and retail chain, which include traceability, inventory management, labour saving costs, security and promotion of quality and safety (Mousavi, Sarhavi, Lenk, & Fawcett, 2002). For example, a Canadian beef producer Atlantic Beef Products (ABP) used hooks embedded with RFID chips to track beef as it was processed throughout its facility (Swedberg, 2006). This system included Psion Teklogix's 7035 handheld RFID interrogator and bar code scanner, Syscan International fixed readers and hooks with embedded 134.2 kHz RFID tags, and Merit-Trax software to integrate reader data into ABP's database. This technology is able to provide the Canadian Food Inspection Agency information on the location of any butchered cow in the plant, as well as maintain an electronic record of what animals are in any package that leaves the plant. This will enable Atlantic Beef to swiftly conduct recalls of all packaged meat specific to a contaminated animal or animals, should this become necessary. In Australia, there was a debate on mandatory implementation of RFID in the National Livestock Identification System (NLIS) to identify and trace the livestock, but a Regulatory Impact Statement released in October 2013 concluded that this "will need to be a substantial investment of resources and funding" (Australian Bureau of Agricultural and Resource Economics and Sciences, 2013),

and therefore, is currently an optional method in the industry.

### 4.2.3    Time-temperature indicators

A time temperature indicator or integrator (TTI) may be defined as a simple, inexpensive device attached onto shipping containers or individual consumer packages that can show a measurable, time-temperature dependent change that reflects the full or partial temperature history of a food product (Taoukis & Labuza, 1989). There are 3 types of commercially available TTIs: critical temperature indicators (show exposure above (or below) a reference temperature), partial history indicators (indicate that a product has been exposed to a temperature sufficient to cause a change in product quality or safety), and full history indicators (a continuous temperature-dependent response throughout a product's history) (Singh 2000). The basic operation principles of TTIs are visible, irreversible responses of mechanical, chemical, electrochemical, enzymatic or microbiological changes of a food product under higher temperatures (Taoukis & Labuza 2003; Smolander, Alakomi, Ritvanen, Vainionpaa, & Ahvenainen, 2004; Kerry, O'Grady, & Hogan, 2006). The extent to which this response corresponds to a real time-temperature history depends on the type of the indicator and the physicochemical principles of its operation. For example, a Vitsab Checkpoint® TTI label is based on a colour change resulting from the controlled enzymatic hydrolysis of a lipid substrate. The TTI can be activated by applying gentle pressure on the "window" to break the seal between the enzyme and substrate mini pouches. A good mixing is recognized by a homogenous green color in the "window (Figure 4). When the dot is green, this represents the packaged foods are under perfect shipping and storage conditions. If the dot is yellow to light orange the product has not been compromised by time/temperature exposure.



**Figure 4. Colour changes of a Vitsab CheckPoint® TTI label (http://vitsab.com/?page_id=2099, access on 10 December 2014, with permission)**

Currently, some examples of marketed TTIs include: 3M TM MonitorMark TM, 3M TM Freeze Watch TM, CheckPoint, Coldmark, ColdSNAP Temperature Recorders, Fresh-Check®, HeatWatch, Log-ic®, Monitor Mark TM, OnVu TM and OnVu Ice, ShockWatch, ThermRF tag, ThermRF Logger, ThermRF Tag, Timestrip®, VarioSens®, and WarmMark Time-Temp Tags. Their working principles and performance are easily accessible through the official websites of the product manufacturers. TTIs can be integrated with barcodes or RFID tags to provide a more convenient and powerful time-temperature record with other product information of the foods. For example, FreshCode™ TTI Smart Barcode is a 1 dimensional standard barcode but also detects and records temperature abuse throughout the supply cold chain (Anonymous 2014b). In 2007, an E.U.-backed project known as Chill-On designed an electronic component that connected TTIs to RFID transponders to lower the supply chain cost of using temperature

sensors in combination with RFID (Wessel, 2007). This system typically includes RFID interrogators mounted inside the backs of trucks or ships. A RFID tag on a package of food (e.g. beef) would record temperature information at regular intervals and transmit the data and the tag's unique ID through GMS and the Internet to a database run by the logistics partner, and then the food's remaining shelf life would be calculated based on the time and temperature information. The TTIs can therefore be used in meat and meat product packaging to monitor the cold distribution chain, microbial safety and quality.

### 4.2.4 Gas indicators

After food packaging, the gas composition within the package often changes as a result of the activity of the food, the package nature, or/and the environmental conditions, such as respiration of fresh produce, gas generation by spoilage microorganisms, or gas transmission through the packaging material or package leaks (Yam, Takhistov, & Miltz, 2005). Gas indicators are small devices in the form of a package label or printed on packaging films that respond to the changes of a gas composition, thereby providing monitoring the quality, safety and integrity of packaged food products. Typically, a gas indicator also induces a color change to reflect the gas composition changes.

Oxygen indicators are the most common gas indicator for food packaging applications as oxygen can cause oxidative rancidity, color change, and microbial spoilage. For example, Mitsubishi Gas Chemical Company produced an Ageless Eye® oxygen indicator that can be inserted inside the container and changes in color from pink to blue when the oxygen concentration is above 0.5% (Figure 5). Another application of oxygen indicators is to detect improper sealing and quality deterioration of modified atmosphere packaged (MAP) foods including pizza and beef (Ahvenainen, Eilamo & Hurme, 1997; Smiddy, Papkovsky, & Kerry, 2002). Gas indicators for carbon dioxide, water vapor, ethanol, hydrogen sulfide, and other gases have also reported. For example, a carbon dioxide indicator consisting of calcium hydroxide (carbon dioxide absorber) and a redox indicator dye incorporated in polypropylene resin has been developed to measure the degree of fermentation in kimchi products during storage and distribution (Hong & Park, 2000), which may be applicable to MAP packaging of meat and meat products. Carbon dioxide indicators were also used to display the desired concentrations of carbon dioxide inside the MAP package (Ahvenainen and Hurme, 1997), which allows incorrectly packaged product to be immediately repacked, and eliminates the need for destructive, labor-intensive and time-consuming quality control procedures (Han, Ho, & Rodrigues, 2005).
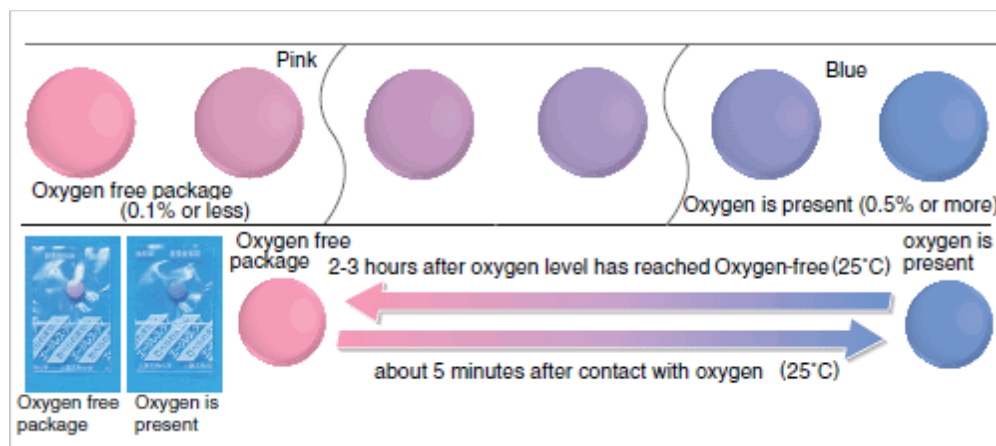


**Figure 5. Ageless Eye® oxygen indicator (http://www.mgc.co.jp/eng/products/abc/ageless/eye.html, access on 10 December 2014, with permission)**

### 4.2.5 Freshness indicators

Of the indicators discussed above, time-temperature indicators and gas indicators show the temperature abuse and gas change/package leakage respectively. An indicator that shows specifically the real spoilage or the lack of freshness of the product would be more ideal for the quality control of packed meat products (Smolander, 2003). Freshness indicators are devices directly indicating the deterioration or loss of freshness of packaged goods (Pereira de Abreu, Cruz, & Paseiro Losada, 2012). The development of freshness indicators is based on established knowledge of quality indicating metabolites specifically associated with the type of meat product, spoilage flora, packaging type and storage conditions. As reviewed by Smolander (2003), the major quality-indicating metabolites or chemicals representing meat freshness are glucose, organic acids (e.g. lactic acid), ethanol, volatile nitrogen compounds, biogenic amines (e.g. tyramine, cadaverine, putrescine, histamine), carbon dioxide, ATP degradation products and sulphuric compounds. Most of the freshness indicators change colour due to the presence of these metabolites or chemicals during spoilage.

A variety of different types of freshness indicators have been described (Smolander 2003; Han, Ho, & Rodrigues, 2005; Kerry, O'Grady, & Hogan, 2006). The most frequently applied in the meat packaging industry are pH dyes (e.g. bromothymol blue) that monitor the formation of carbon dioxide generated as a result of microbial growth (Holte, 1993). The increased carbon dioxide levels react with the pH dyes and change the colour. Other pH dyes that have been proposed for the same purpose are xylenol blue, bromocresol purple, bromocresol green, cresol red, phenol red, methyl red and alizarin (Horan 2000). Besides carbon dioxide, other metabolites including $SO_2$, $NH_4$, volatile amines, and organic acids have been used as target monitoring molecules using pH-sensitive indicators (Smolander, 2003).

A glucose sensor-based meat freshness indicator has been invented by Kress-Rogers (1993) using the principle that the glucose level on the meat surface is reduced through its utilisation by microorganisms during their growth. Hydrogen sulphide is produced during the spoilage of meat and meat products by a number of bacterial species. A meat freshness indicator has been developed based on the concept that hydrogen sulphide is able to bind myoglobin to form a green pigment, sulphmyocin (Smolander, Hurme, Latva-Kala, Luoma, Alakomi, & Ahvenainen, 2002). Interestingly, this indicator is specifically detects the formation of hydrogen sulphide and is not affected by the presence of nitrogen or carbon dioxide. Another example of meat freshness indicators is a diamine dye-based sensor system in which diacetyl, a volatile metabolite of bacterially spoiled meat, migrates through the permeable meat package to react with the dye and change its colour (Honeybourne, 1993).

### 4.2.6 Pathogen indicators and biosensors

In addition to the systems discussed above that react to the spoilage of food products, indicators to detect the contamination by pathogenic microorganisms of meat and meat products have also been developed. These pathogen indicators are biosensors which are compact analytical devices detecting, recording, and transmitting information pertaining to pathogen-induced biochemical reactions (Yam, Takhistov, & Miltz, 2005). These devices consist of a bioreceptor that recognizes a target analyte and a transducer that converts biochemical signals into a quantifiable electrical response. Bioreceptors are organic or biological materials such as an enzyme, antigen, microbe, hormone, or nucleic acid, while transducers include electrochemical, optical and calorimetric, depending on the system. These pathogen indicators/sensors also change color in the food package to warn consumers/retailers that food must not be consumed.

A specific sensor for the detection of E. coli O157 enterotoxin has been developed by Quan and Stevens

(1998). The sensor is composed of cross-polymerized polydiacetylene molecules that can bind the toxin to cause the color of the packaging film to change permanently from blue to red (Smolander, 2000). One commercially available pathogen indicator is called Food Sentinel SystemTM (SIRA Technologies, California, USA) that shows the presence of pathogens in meat packages (Goldsmith, Goldsmith, Woodaman, Park, & Ayala, 1999). In this system, an antibody specific for the target pathogen (eg. Salmonella sp., E. coli 0157:H7, L. monocytogenes) is attached to a membrane that forms part of the barcode; the presence of contaminating pathogen will cause the formation of a localized dark bar, rendering the barcode unreadable upon scanning. Toxin GuardTM developed by Toxin Alert (Ontario, Canada) is another pathogen indicator consisting of biochemical sensors incorporating antibodies in a polyethylene based plastic packaging (Bodenhamer 2000). This system is able to detect pathogens such as Salmonella sp., Campylobacter sp., E. coli, and Listeria sp., bacterial degradation. Moreover, this device is also able to detect chemicals such as pesticides, and genetic modification markers (Pereira de Abreu, Cruz, & Paseiro Losada, 2012).

### 4.2.7 Patents of intelligent packaging

Some of the patents in this area (Goldsmith et al., 1999; Bodenhamer, 2000; Quan & Stevens, 1998) have already been discussed above. In the last ten years however, there have considerable innovative ideas with new patent registrations in the intelligent packaging area. The basic operation principles of all of these indicators and sensors are similar to that of the TTIs, i.e. visible irreversible responses of mechanical, chemical, electrochemical, enzymatic or microbiological changes of a food product under different packaging conditions. Mnay of these devices have the potential to be used in meat packaging.

A microbial based time-temperature indicator was invented by Lu, Jia, and Cai (2011) with the concept that the pH dye (0.1% bromocresol green + 0.2% methyl red ethanol solution) changes colour when L. casei sp. Rhamnosus GG grows in the media under the suitable temperature. A TTI based on lipase reaction diffusion was also invented by the same group (Lu, Cai, & Zheng, 2011). In this TTI, the enzymatic reaction forms a yellow area and the diffusion length of the yellow area is dependent on the time and temperature exposure that the packaged product has experienced. De La Puerta, Gutierrez, & Sanchez (2010) invented a novel smart packaging using vanillin as colorimetric reagent for the detection of microbial growth visual vapour. This system allows the growth of microorganisms in different types of products to be detected visually without having to be in direct contact with the microorganism or with the medium containing them. To detect the oxygen gas concentration in the food packaging, a nano $TiO_2$ powder was prepared and mixed with electron donors, oxidation-reduction dyes and polymers in the packaging film (Liu, Xie, Zhou, Yang, & Li, 2013), which has the potential to be used in MAP meat product to monitor the oxygen level during cold storage.

Similar to a RFID system, an intelligent packaging system utilizing acoustic wave devices including an electronic module, a surface acoustic wave (SAW) ID, various passive SAW sensors and a printed antenna was invented by Georgescu, Cobianu, & Dumitru (2008). The advantage of this improved system is that it is able to monitor various physical and chemical parameters of the contents of a package during transport, storage and throughout a supply chain. More recently, smartphone recognizable internet based intelligent packaging has attracted great interest. A 2 D barcode has been designed which includes graphics, lines and even characters that decoded the information (product origin, manufacturing date etc.) of the packaged food product (Wang, Xu, Jiang, & Liu, 2013). Consumers can access the detailed information of the product by scanning the barcode using their smartphone. Interestingly, a voice advertisement intelligent packaging was invented by Zhai (2010). The packaging contains a small battery,

a voice chip integrated circuit and a loudspeaker. When the package is open, the voice about the product information or/and music is played which can prevent the forgery and even animate and improve the consumers' dining experience.

## 4.3    Edible coatings and films and biodegradable packaging in meat industry

Edible coatings or films are defined as continuous matrices prepared from edible materials made up of proteins, polysaccharides and lipids. Edible coatings are either applied to or made directly on foods while films are independent structures. These coatings and films are located on the food surface or as thin layers between several parts within the product with the aim of improving overall food quality and extending shelf-life by functioning as barriers to moisture, gas and solute transmission. Moreover, they can be used to incorporate functional food substances, such as antimicrobials, antioxidants, flavouring agents and nutrients, to improve safety, stability, sensory, and nutritional properties of foods (Lin and Zhao, 2007; Silva-Weiss et al., 2013).

With regard to meat and meat products, edible coatings and films not only help reduce the rate of moisture and gas transfer, but more importantly, can incorporate antimicrobial and antioxidant agents to prevent contamination by and growth of both pathogenic and spoilage organisms, and thus delay lipid oxidation. In this way the edible coatings and films can help ensure quality, microbial safety and extend the shelf-life of meat and meat products.

Khan et al. (2013) recently reviewed the application of various types of lipid, polysaccharide and protein-based edible coatings, as well as multicomponent edible coating systems on meats, poultry, and seafood, and summarized the potential benefits of edible coating on meat and meat products as follows:

- Edible coatings with good moisture barrier properties could help alleviate the problem of moisture loss.

- Edible coatings could hold in juices, prevent dripping, enhance product presentation, and eliminate the need for placing absorbent pads at the bottom of trays.

- The rate of rancidity-causing lipid oxidation and myoglobin oxidation in meats could be reduced by using edible coatings of low oxygen permeability, although not so low as to create anaerobic conditions.

- Edible coatings could reduce the load of spoilage and pathogenic microorganisms and partially inactivate deteriorative proteolytic enzymes at the surface of coated meat.

- Edible coatings could control the loss of volatile flavour compounds and prevent the pick-up of foreign odours.

- Edible coatings incorporating antioxidants and/or antimicrobials can be used for direct treatment of meat surfaces, thereby delaying meat rancidity and discoloration, and reducing microbial loads.

- Edible coatings applied on the surface of meat pieces prior to battering, breading, and frying, could improve the nutritional value of the product by reducing oil uptake during frying.

Biobased packaging materials are defined as materials derived primarily from annually renewable sources. This definition excludes paper-based materials because, although obviously biobased, trees generally have renewal times of 25–65 years (Robertson, 2013; Robertson, 2014). Due to growing environmental concerns and petroleum costs, there is an increasing demand for identifying biodegradable

packaging materials and finding innovative methods to make plastic biodegradable. Several biodegradable packaging materials with or without other functional compounds have been used to package meat and products (Kuorwel et al., 2011; Sung et al., 2013; Lim and Wan Rosli, 2014; Muppalla et al., 2014).

The follwing sections of this review provide an overview of different edible and biodegradable packaging materials and their corresponding properties when used as coatings and films. Antimicrobial coatings for meat and meat products are discussed. In addition, recent research and patents in edible coatings and films and biodegradable packaging on meat and meat products are reported.

## 4.3.1 Materials for making edible coatings and films

Many publications have discussed the materials and formulations for making edible coatings and films (Lin and Zhao, 2007; Vargas et al., 2008; Khan et al., 2013; Maftoonazad et al., 2013; Silva-Weiss; Sánchez-Ortega et al., 2014). Biopolymers such as polysaccharides, proteins and lipids can be used alone or in combination to form coatings and films, the physical and chemical properties of the base materials, greatly influencing the functionality of the films and coatings produced. The choice of materials is generally based on their water solubility, hydrophilic and hydrophobic nature, easy formation into coatings and films, sensory properties, and targeted applications. Some coating materials, such as chitosan, have inherent antimicrobial and antioxidant functions, which make them more attractive as coating and film forming materials. Some minor components, usually plasticizers (such as glycerol and sorbitol) and acids (such as acetic or lactic acid), are added into the formulation for improving coating or film flexibility and regulating pH (Duan and Zhao, 2010). The following sections briefly describe the common coating and film forming materials and the functionality of the resulting coatings and films.

**1). Polysaccharide-based edible films and coatings**

Polysaccharides, such as cellulose and its derivatives, starch, chitosan, and pectin have been commonly used to make edible coatings and films. Polysaccharide based coatings and films provide a good barrier to $O_2$ and $CO_2$, but a poor barrier to water vapour due to their hydrophilic nature. On the molecular level, polysaccharides vary in molecular weight, degree of branching, conformation, electrical charge, and hydrophobicity, which leads to variations in their ability to form coatings and films and in the physicochemical properties and performance of coatings and films they produce (Vargas et al., 2008).

Cellulose and derivatives - Cellulose is the most abundant natural biopolymer on earth. It is composed of D-glucose units through β-1,4 glycosidic bonds, and is insoluble in water in its native form. The water solubility of cellulose can be improved by alkali treatment to swell the structure, followed by reaction with chloroacetic acid, methyl chloride, or propylene oxide to yield carboxymethylcellulose (CMC), methylcellulose (MC), hydroxypropyl methylcellulose (HPMC), or hydroxypropyl cellulose (HPC). These derivatives have different permeability to water vapor and gases, and are good film formers due to the linear structure of their polymer backbone. They can be dissolved in aqueous or aqueous-ethanol solutions to produce coatings and films that are water soluble but resistant to fats and oils (Lin and Zhao, 2007).

Chitosan and derivatives - Chitosan, one of a few natural cationic polysaccharides, is the N-deacetylated derivative of chitin. Chitin exists in three morphologically distinct forms as α, β, and γ. α-Chitin is mainly sourced from shrimp, crab, and krill shells, β-chitin is sourced from squid pens, and γ-chitin is usually derived from fungi and yeast. Chitosan-based coatings and films have selective permeability to $O_2$ and $CO_2$, and good mechanical properties, but high water vapour permeability. Chitosan directly inhibits the

growth of a wide variety of bacteria and fungi since its positively charged structure can interact with the negatively charged microbial cell membranes, inducing leakage of cellular constituents such as proteins (Devlieghere et al., 2004; Jung et al., 2013). The antioxidant activity of chitosan is also well reported. Chitosan can scavenge free radicals or chelate metal ions. The hydroxyl groups (OH) and amino groups (NH2) in chitosan are the key functional groups for its antioxidant activity (Jung and Zhao, 2012). Moreover, when forming into films or coatings, chitosan can effectively carry other functional substances, such as nutraceuticals, antioxidants, and antimicrobial agents, due to the presence of a high density of amino groups and hydroxyl groups in the chitosan polymer structure (Park et al., 2004).

Elsabee and Abdou (2013) recently provided a comprehensive review on the application of chitosan and its blends with other natural polymers (eg. starch, essential oils and clay) as edible coating and films for food protection. The mechanical behavior and the gas and water vapor permeability of the films were also discussed. References dealing with the antimicrobial behavior of these films and their impact on food protection were explored. The examples of chitosan based coatings on meat and meat product are presented later in this review.

Starch and its derivatives - Starch is commonly used for making edible coatings and films because of its abundance, biodegradability, wide range of functionality, and relatively low cost. Starch films are often transparent or translucent, odourless, tasteless, and colourless, and have good mechanical properties and low permeability to O2 at low-to-intermediate relative humidity. However, ther are only a few reports on the use of starch-based coatings on meat and meat products.

Pectin - Pectin, a complex group of structural polysaccharides found in plants, is mainly composed of D-galacturonic acid polymers with varying degrees of methyl esterification. When dissolved in aqueous media, pectin is able to form a gel in the presence of calcium ions, which bridge free carboxyl groups on adjacent polymer molecules. Once the polymer chains are aligned, hydrogen bonding between neighbouring chains strengthens the association, and the films or coatings can then be formed by evaporating the excess water (Kester and Fennema, 1986). Pectin-based coatings and films have a somewhat glossy, non-sticky surface, and generally have high water vapour permeability due to their hydrophilic nature. Recently, pectin extracts from fruit processing by-products, such as apple and citrus fruit pomace, have been used to make edible coatings and films with antimicrobial and antioxidant properties due to the residual phenolics compounds from the pomace (Deng and Zhao, 2011).

Seaweed extracts – Alginates extracted from brown seaweeds (Phaeophyceae) also possess good film-forming properties. The transparent and water-soluble alginate-based films are impervious to oils and fats, but have high water vapour permeability. The ability of alginates to react with di- and tri-valent cations such as sodium, calcium, magnesium, aluminium, and ferrous ions is being utilized in alginate film formation. Carrageenan is another water-soluble galactose polymer extracted from several red seaweeds, mainly Chondrus crispis. Carrageenan film formation involves a gelation process the polysaccharide double-helix during moderate drying of the polymer solution, which leads to a formation of a three-dimensional polymer network after residual solvent evaporation (Kester and Fennema, 1986).

## 2). Protein based edible films and coatings

Proteins of both plant and animal origin can form coatings and films with good mechanical properties and O2 and CO2 barrier functionality, particularly at low relative humidity. These coatings and films however, exhibit relatively poor water-barrier characteristics and are brittle and susceptible to cracking due to the strong cohesive energy density of the polymer. Plasticizers can be incorporated into protein-based

coatings and films to reduce britleness and improving their flexibility.

Plant origin - Corn zein, the prolamin fraction of corn protein, is insoluble in water except at very low or high pH due to its high content of nonpolar amino acids. Corn zein coatings and films possess a good oxygen barrier and relatively good water barrier properties. However, plasticizers are required to improve the extensibility of the films. Soy protein as soy protein concentrate (SPC, 70% protein) or soy protein isolate (SPI, 90% protein) have been made into coatings and films with potent oxygen barrier but poor moisture barrier properties due to the inherent hydrophilicity of the proteins. Heat treatment is often used to enhance coating or film formation by partially denaturing the protein to allow formation of disulfide bonds. Similarly, acidic or alkaline conditions facilitate soy protein denaturation and promote disulfide bond fomation in dried coatings or films (Park et al., 2002). Wheat gluten protein is soluble in aqueous alcohol, but alkaline or acidic conditions are required for the formation of homogeneous coatings or films. These coatings and films have high water permeability due to their hydrophilic nature but are good barriers to O2 and CO2 (Baldwin, 2007).

Animal origin - Casein (80% of total milk protein), whey protein (20% of total milk protein), and their combination have been used to make coatings and films. Caseins can form colourless, flavourless and flexible films from aqueous solutions without further treatment. Casein based coatings and films are resistant to thermal denaturation and/or coagulation, thus remaining stable over a wide range of pH, temperature, and salt concentration (Khwaldia et al., 2004). With heat denaturation and addition of plasticisers, whey proteins produce transparent and flexible water-based edible films and coatings with excellent oxygen, aroma, and grease barrier properties at low relative humidity (Lin and Zhao, 2007). Collagen, the major component of skin, tendon and connective tissues in animals, has traditionally been used in the meat industry for edible sausage casings. Gelatine is the protein derived by partial hydrolysis of collagen. When dissolved in aqueous solutions, gelatine can form flexible, clear, strong and oxygen-permeable films by formation of ionic crosslinks between amino and carboxyl groups of amino acid side chains (Nur Hanani et al., 2014).

When applied on raw meat, protein based coatings and films may encounter problems due to their susceptibility to proteolytic enzymes present in meat. Moreover, food allergy to proteins needs to be considered in terms of consumer acceptance and food labelling requirements (Gennadios et al., 1997).

**3). Lipid-based edible films and coatings**

Lipid based coatings and films are very effective moisture barriers due to their hydrophobic character, and are used primarily to inhibit moisture loss from foods and to improve consumer appeal by adding a glossy finish to the treated products. A wide variety of lipid compounds including natural waxes, acetylated monoglycerides, fatty acids, and resins are commonly utilised.

Natural waxes, such as carnauba wax, beeswax, paraffin wax, and candelilla wax, are considered generally recognized as safe (GRAS) in the United States (Baldwin, 2007). Wax coatings have been traditionally applied to fresh fruit and vegetables for extending postharvest storage life. They are substantially more resistant to moisture transport than most other edible coatings. Acetylated monoglycerides have been applied to poultry and meat to protect against dehydration during cold and frozen storage (Stuchell and Krochta, 1995; Mate et al., 1997). Most fatty acids, such as capric, lauric, myristic, oleic, palmitic, and stearic acids, that are derived from vegetable oils are considered GRAS, and are commonly used with glycerides as emulsifiers in the preparation of edible coatings and films (Baldwin, 2007). Resin (e.g. shellac and terpene resin) based coatings generally have lower permeability to O2, CO2 and ethylene gas, and

moderate permeability to water vapour (Baldwin, 2007). Shellac coating dries rapidly, a high gloss appearance to the coated product (Lin and Zhao, 2007), and is approved by US Food and Drug Administration (FDA) as a safe food coating material (Hagenmaier and Shaw, 1991).

Lipid-based coatings and films provide a good moisture barrier, but poor mechanical properties, poor adherence, a greasy surface, waxy taste and lipid rancidity may occur. Lipids are usually applied in combination with polysaccharides or proteins to form composite coatings and films for taking advantage of the special functional characteristics of each component.

### 4). Composite and multi-component coatings and films

Each coating or film forming material has some unique but also limited functions. The composite or multi-component coatings or films can take advantage of the special functional characteristics of individual materials for enhancing their functionality (Wu et al., 2002). Composite coatings and films can be categorized as bilayer or emulsified coatings and films. The formation of composite coatings and films involves casting or laminating a lipid onto a dried protein or polysaccharide film, whereas the latter involves dispersing the lipid into the coating and film forming solution prior to its casting. (Lin and Zhao, 2007). In general, bilayer coatings and films are more effective water vapour barriers due to the existence of a continuous hydrophobic phase in the matrix. However, emulsified coatings and films have received more interest for industrial application because they need only one drying step instead of the two steps necessary for the bilayer coatings and films. Examples of composite and multi-component coatings and films include polysaccharide-lipid composites (eg.: starch with sunflower oil; cellulose with fatty acid; corn starch with methylcellulose, cocoa butter, or soybean oil), protein-lipid composite (eg.: whey protein with fatty acid; wheat gluten with beeswax or paraffin wax; gelatine with resinous oil), polysaccharide-protein composite (eg. alginate with soy protein isolate), polysaccharide-polysaccharide composite (eg. chitosan with starch) and protein-protein (eg. soy protein isolate with and gelatine) (Lin and Zhao, 2007). More detailed discussion and examples of the composite coatings and films can be found from Wu et al. (2002), Lin and Zhao (2007), Duan and Zhao (2010), and Maftoonazad et al. (2013).

### 4.3.2 Antimicrobial edible coatings and films for meat and meat products

While edible coatings and films can provide multiple functions for meat and meat product packaging, there is increased interest in the development and usage of antimicrobial edible coatings and films to preserve meat quality for longer shelf life and improved food safety. Incorporation of antimicrobial compounds into edible coatings and films as an alternative to their direct application onto the meat surface has the advantage of gradual release of the antimicrobial compounds. This permits a reduction in the level of added antimicrobial which in turn reduces any negative antimicrobial-related sensory changes.

Antimicrobial agents commonly incorporated into edible coatings and films for meat and meat products include organic acids (lactate and acetate, malic acid, propionate, and p-aminobenzoic acid), essential oils and plant extracts (lemongrass, oregano, pimento, thyme, or cinnamon), bacteriocins (nisin, pediocin), enzymes (lysozyme), chitosan and lauric arginate (Sung et al., 2013).

Plant-derived essential oils as natural antimicrobial agent in preservation of meat and meat product have attracted great interest due to their remarkable antimicrobial potency against both spoilage and pathogenic microorganisms (Jayasena and Jo, 2013). Essential oils contain low molecular weight compounds such as terpenes, terpenoids, and aliphatics. Oils containing phenols such as thymol, carvacrol, and eugenol exhibit the highest activity against a broad spectrum of microorganisms. Their

antimicrobial mechanism of action is attributed to their ability to disrupt the microbial cytoplasmic membrane. Incorporation of essential oils in the formulation of edible coatings and films applied to meat products is expected to reduce their bacterial population. However, essential oils are sensitive to temperature, oxygen and light, and also have distinctive odours; therefore they may not be stable and may alter the sensory characteristics of the coated products. Microencapsulation of essential oils or natural ingredients in which they are present has been used as an alternative approach to protect them from interaction with environmental factors, avoiding their oxidation or volatilization whilst not inhibiting their antimicrobial effect. Moreover, encapsulation increases the solubility of essentials oils in water, allows their release only at the desired stage, and makes them easier to handle during storage and transportation (Jayasena and Jo, 2013).

The effectiveness of antimicrobial coatings and films for meat applications depends on the meat source, polymer used, film barrier properties, target microorganism, antimicrobial substance, and storage conditions. Sánchez-Ortega et al. (2014) reviewed the studies on using antimicrobial edible coatings and films for the preservation of various meat and meat products. While they are a good alternatives to improve the quality and safety of meat and meat products, there are some challenges remaining, such as the need to improve and standardize coating procedures according to industry requirements, to reduce costs, to increase shelf life and to prevent the potential alteration on the sensory characteristics of the packaged product. The different characteristics of the wide range of meat and meat products make it very difficult to standardize a single application procedure. Meanwhile, the different compositions and properties of various antimicrobial edible coatings provide different functionalities which may be affected when scaling up of application methods for commercial operations (Sánchez-Ortega et al., 2014).

### 4.3.3 Recent research development on edible coatings for meat and meat products

Several review articles have provided many examples of edible coatings for meat and meat products (Duan and Zhao, 2010; Khan et al., 2013; Sánchez-Ortega et al., 2014). This section summarizes the most recent studies on using these edible coatings and films.

Chitosan is one of the most studied coating materials for meat and meat products due to its inherent antimicrobial and antioxidant properties as previously discussed. Baranenko et al. (2013) developed chitosan coatings with gelatin, distarch glycerol, wheat fibre, sodium alginate, or guar gum in various ratios and applied them to the surfaces of retail cuts of veal and rabbit meat, boiled sausages, smoked sausages and smoked-boiled pork brisket stored at 4 ±1°C. All coatings reduced the total viable counts of microorganisms compared to uncoated samples. Coatings based on 2% chitosan and 2% gelatin solution in a ratio of 1:1 showed the strongest bacteriostatic effect against B. subtilis, S. aureus and E. coli. Combined application of vacuum and protective coatings provided the strongest suppression effect in all samples. Kanatt et al. (2013) investigated the effect of a 2% chitosan coating on the shelf life of ready-to-cook meat products (chicken balls, chicken seekh kababs and mutton seekh kababs) stored at 3 oC for 14 days.

The chitosan coating eliminated fecal coliforms, lowered counts of B. cereus, S. aureus, E. coli, and P. fluorescens, and retarded lipid oxidation in all the meat products during storage. In addition, no significant organoleptic changes in the chitosan-coated samples were observed. Bonnia et al. (2014) prepared 1% chitosan films with and without basil or thyme essential oils (0.5 or 1% wt) and used them as a cup containing fresh port fat stored at 40 oC and 43% and 83% relative humidity. Chitosan films showed good oxygen barrier properties which however decreased when essential oil was added; especially when the film equilibrium moisture content increased. All of the films effectively protected pork fat from oxidation,

and the films with essential oils were more effective than those of pure chitosan.

Films have alos been reported as effective to control growth of E. coli and L. innocua in minced pork meat stored at 10 oC, but the incorporation of essential oils did not improve their antimicrobial activity. Guo et al. (2014) applied 2 or 5% chitosan coating with lauric arginate ester (LAE), sodium lactate (NaL), and sorbic acid (SA) alone or in combinations onto polylactic acid (PLA) films for packaging deli turkey -meat stored at -20 oC. Antimicrobial PLA films containing 1.94 mg/cm2 of chitosan and 1.94 μg/cm2 of LAE reduced L. innocua, L. monocytogenes, and S. typhimurium to undetectable levels on the meat during 3 and 5 weeks of storage at 10 °C, thus achieving a 2–3 log reduction of Listeria and 1–1.5 log reduction of Salmonella as compared with controls.

He et al. (2014) developed chitosan (Ch) coating with incorporation of clove oil (CO) and/or ethylenediaminetetraacetate (E) and applied this on lean sliced pork stored at 4 oC for 1 week. Ch + CO + E solution exhibited the highest inhibition rates of E. coli and S. aureus (99.17 and 96.42%, respectively). CO and/or E incorporated chitosan coatings could moderate the growth of total microbes and maintain acceptable sensory characteristics of pork in 7 days of storage at 4 oC. The coatings of Ch, Ch + CO and Ch + CO + E improved both lightness and red colour stability of pork. Dehnad et al. (2014) developed 1% chitosan-nanocellulose (0.18% w/w) biocomposites. The agar disc diffusion method demonstrated that the nanocomposite had inhibitory effects against both gram-positive (S. aureus) and gram-negative (E. coli and S. enteritidis) bacteria through its contact area. The coatings when applied to ground meat, decreased lactic acid bacteria population compared with nylon packaged samples by up to 1.3 and 3.1 log cycles at 3 and 25 °C respectively after 6 days of storage.

In addition to chitosan, other coating materials, alone or in combination have also been studied. Rakshit and Ramalingam (2013) evaluated gum acacia coatings containing garlic or cinnamon on fresh chicken piece stored 5 °C for 3 weeks. The minimum inhibitory concentration (MIC) against 5 spoilage and pathogenic bacteria (E. coli, P. mirabilis, S. aureus, E. faecalis and B. cereus) was found to be between 0.03 to 0.288 mg/mL and 0.061 to 0.24 mg/mL for garlic and cinnamon, respectively. The shelf life of the meat was increased by three weeks at 5 °C by using these coatings. Weerasinghe et al. (2013) applied a whey protein concentrate coating, with and without enzymatically hydrolyzed casein on cubed beef steak stored at 4 oC for 8 days. Lipid oxidation was significantly reduced by coating treatments and the carbonyl content of all treatments was lower than controls and blanks during storage .

Thiols and key sensory attributes were also significantly protected by the coatings throughout the storage period. Han et al. (2014) investigated the use of films consisting of cast polypropylene/polyvinyl alcohol with rhubarb ethanolic extracts (REE) and cinnamon essential oil (CEO) in maintaining fresh beef steak quality during storage at 4 °C ± 1 °C. All films significantly inhibited bacterial growth and maintained the pH and total volatile basic nitrogen (TVB-N) of beef steaks with the optimum coating containing 1% (v/v) REE and 0.08% (v/v) CEO. Morsy et al. (2014) evaluated the effectiveness of pullulan films (5% to 10%, w/v) containing 2% oregano or 2% rosemary oil and metallic nanoparticles (100 nm Ag or 110 nm ZnO) against S. aureus, L. monocytogenes, E. coli O157:H7, and S. Typhimurium.

Those films containing 2% oregano or rosemary oil and 110 nm ZnO effectively inhibited the four pathogens on vacuum packaged meat (raw beef, raw turkey breast and ready-to-eat turkey deli meat) stored at 4 °C for up to 3 weeks. Zimoch-Korzycka and Jarmoluk (2014) applied edible hydrosols (hydroxypropylmethylcellulose (HPMC), chitosan, lysozyme and nanocolloidal silver) on the surface of bovine tenderloin stored at 4 oC. The hydrosols caused death of each tested microorganism (B. cereus, M. flavus, E. coli and P. fluorescens) with simultaneous influence of chitosan, lysozyme and nano-Ag and

storage time on total number of bacteria in meat samples with hydrosols was observed. In addtion of lysozyme to the hydrosols also significantly increased their antioxidant activity.

### 4.3.4 Biodegradable packaging

Biodegradable packaging materials are defined as materials derived primarily from renewable sources, such as replenishable agricultural feedstocks, animal sources, marine food processing industry wastes, or microbial sources, and can break down to produce environmentally friendly products such as carbon dioxide, water, and quality compost (Tharanathan 2003; Robertson, 2013, 2014). Biodegradation is the process by which carbon-containing chemical compounds are decomposed in the presence of enzymes secreted by living organisms, and requires appropriate temperature, humidity and type of microbes for a rapid degradation process.

Due to growing environmental concerns and increasing petroleum costs, there is great interest in identifying biodegradable packaging materials and finding innovative methods to make plastic degradable. According to Mohan (2010), the total consumption of biodegradable polymers in North America, Europe, and Asia was forecast to grow at an average annual rate of nearly 13% over the five-year period from 2009 to 2014. The report from market research firm Global Industry Analysts predicted that the global market for biodegradable polymers will reach 1.1 million tonnes by the year 2017. Europe continues to be the largest biodegradable polymers-consuming region, utilising about half of the global total.

According to Mahalik and Nambiar (2010), acceptable biopolymers include:

Cellulose: Isolated from its crystalline state in microfibrils by chemical extraction, it is fusible and soluble in hydrogen bond-breaking solvents such as N-methylmorpholine-N-oxide. Because of its infusibility and insolubility to others, its derivatives can also be used to make it more processable.

Starch: Biodegradation of starch-based polymers is due to enzymatic attack at the glycosidic linkages between the sugar groups, leading to a reduction in chain length and splitting out of lower molecular weight sugar units. As regards to its application in biodegradable plastics, it is either physically mixed with its native granules or melted and blended on a molecular level with the appropriate polymer.

Polylactide acid (PLA): PLA is emerging as one of the most attractive packaging material because of its excellent biodegradability, processability, and biocompatibility. PLA is a biodegradable thermoplastic derived from renewable resources such as the corn starch. PLA is processed by injection molding, blow molding, thermoforming, and extrusion. Its degradation is dependent on time, temperature, low molecular weight impurities, and catalyst concentration. PLA films have better ultraviolet light barrier properties than low density polyethylene (LDPE) but lower melting and glass transition temperatures.

Poly-beta-hydroxyalkanoates (PHB): A member of poly hydroxyl alkanoates, degrades under the presence of various microorganisms which upon contact with the polymer secrete degradative enzymes. The three most unique properties of PHB are (i) 100% resistance to water, (ii) 100% biodegradability, lower melting and glass transition temperatures than LDPE, and (iii) thermoplastic process ability.

Polycaprolactone (PCL): A biodegradable polyester with a low melting point of around 60 °C and a glass transition temperature of about −60 °C. Its most common use is in the manufacture of specialty polyurethanes. Polycaprolactones impart good water, oil, solvent and chlorine resistance to the polyurethane produced.

Poly(3-hydroxybutyrate-co-3-hydroxyvalerate) (PHBV): As a polyhydroxyalkanoate-type polymer, it is biodegradable, nontoxic, biocompatible plastic, produced naturally by bacteria and a good alternative for many non-biodegradable synthetic polymers. It is a thermoplastic linear aliphatic polyester.

Gelatin: Gelatin from different sources have different physical and chemical properties since they contain different amino acid contents. This leads to varying characteristics upon being utilized in the manufacture of films. Packaging films can be successfully produced from all gelatin sources and the behaviour and characteristics of gelatin-based films can be altered through the incorporation of other food ingredients to produce composite films possessing enhanced physical and mechanical properties (Hanani et al., 2014).

Kuorwel et al. (2011) reported on the biodegradable polymers derived from polysaccharides and protein-based materials for their potential use in packaging systems designed for the protection of food products from microbial contamination. A comprehensive table that systematically analyses and categorizes the current literatures in this area was provided. Khan et al. (2014) discussed the potential use of nanocellulose (NC) fiber-based nanocomposite with the incorporation of bioactive agents, such as antioxidants and antimicrobials in developing biodegradable food packaging, to extend shelf-life and improve food quality. The NC fiber-based films are biodegradable, relatively cheap, lightweight, and very strong.

### 4.3.5 Biodegradable packaging for meat and meat products

There are currently a range of commercially available biodegradable containers for meat and meat products. Among them, IngeoTM biopolymer by NatureWorks LLC. (Blair, Nebraska, USA) is mostly used to make foam trays. IngeoTM biopolymer uses dextrose (sugar) from corn as the primary feedstock (PLA), but can be made from any abundantly available sugar. Some commercially available biodegradable packaging for meat and meat products are presented in Table 13.

**Table 13. Some commercially available biodegradable packaging for meat and meat products**

| Products and manufacturer | Description |
|---|---|
| Back 2 Earth, Ridgeland, SC, USA | Meat trays made completely from wheat stalk and are GMO- and gluten-free. |
| BASF Co., Florham Park, New Jersey, USA | A new foaming grade of Ecovio biopolymers. Blends of BASF's petrochemical-based Ecoflex biodegradable resin with PLA. |
| BioMass Packaging™, Richmond, CA, USA | Foam trays made from Ingeo® |
| Bodin Industries, France | Foam trays made from PLA resin, and used to package meat or fish at the Finiper SpA super-market chain in Italy and organic chicken or duck. |
| BuyGreen, Irvine, CA, USA | Biodegradable trays made from corn polymers, starches and complementary ingredients to create a blend that is 100% biodegradable and microwave and freezer safe. |
| Clear Lam Packaging, Inc., Elk Grove Village, IL, USA | Made from Ingeo™ biopolymer to package a variety of meats, cheeses, pastas, egg rolls and other perishable food items. |
| Coopbox SpA, Reggio Emilia, Italy | The first foam PLA trays, called Naturalbox, in 2005 for meat, fish, or poultry. |
| Cryovac® Food Packaging Systems, SC, USA | NatureTRAY™, foam trays made from Ingeo™ and used to package meats, fish, poultry, and produce. Fully moisture resistant. |
| Dyne-A-Pak Inc., Laval, QC, Canada | Use Ingeo™ biopolymer (PLA) supplied by NatureWorks LLC with lightweight and efficiency of a foam packaging for meat, produce and deli. |

| | |
|---|---|
| GreenGood Eco-Tech Company Lt., Hong Kong | Foam trays made from Ingeo™ |
| Greenus, Hanchang Paper, Seoul, South Korea | Foam trays made from Ingeo™ |
| Novamont, Italy | The first commercialized non-water-soluble Mater Bi™ (starch-based) foam trays in 2004. Foamed with gas rather than chemical blowing agent. Have the advantage of being backyard compostable. Used for foam food trays in Europe. |
| Sirap Gema SpA, Verolanuova, Italy | Foamed Ekofoam trays out of Mater-Bi™. |
| WeiYi Packaging Co, LLD, Guangdong, China | Made from Ingeo™. Biodegradable food grade high barrier cook meat vacuum packaging. Provide biodegradable strong roasted meat packaging bag. |
| Winfa Packaging Co., Ltd, Hong Gong | Meat trays made from Ingeo™. |

### 4.3.6 Recent research development in biodegradable packaging for meat and meat products

This section will briefly summarise the most recent research developments (2013-2015) in biodegradable packaging for meat and meat products.

Woraprayote et al. (2013) developed a novel PLA/sawdust particle (SP) biocomposite film with anti-listeria activity by incorporation of pediocin PA-1/AcH (Ped). The anti-listeria activity of this film was detected, while no activity against the tested pathogen was observed for the control PLA films. Dry-heat treatment of the film before coating with Ped resulted in the highest Ped adsorption (11.63 ± 3.07 µg protein/cm2) and the highest anti-listeria activity. A model study of PLA/SP + Ped as a food-contact antimicrobial packaging on raw sliced pork suggested a potential inhibition of L. monocytogenes (99% of total listerial population) on raw sliced pork during chilled storage.

Amna et al. (2014) developed a new class of antimicrobial hybrid packaging mat composed of biodegradable polyurethane supplemented with virgin olive oil and zinc oxide via electrospinning. Results indicated that the nanocomposite packagings were able to inhibit growth of S. aureus and S. typhimurium, and could replace PVC film meat packaging.

Biodegradable packaging produced from cornstarch, linear low-density polyethylene (LLDPE), and citric acid (CA) for beef packaging was developed by Junior et al. (2014) . Packaged beef samples stored under refrigeration showed a significant reduction in the levels of lipid oxidation and 1-log decrease in total bacterial count, compared with the control film. Redness of beef color was also increased.

Kanatt et al. (2014) prepared films from chitosan (Ch) and polyvinyl alcohol (PVA) containing aqueous mint extract (ME)/pomegranate peel extract (PE). Addition of ME/PE improved the tensile strength of the films without affecting their puncture strength. Ch–PVA films incorporated with PE had the highest tensile strength (41.07 ± 0.88 MPa). The films also exhibited antibacterial activity against S. aureus and B. cereus. PE containing films totally inhibited the growth of B. cereus and reduced the number of S. aureus by 2 log cycles.

Lim and Rosli (2014) packed beef patties with either non-biodegradable high density polyethylene (PE), hydro-biodegradable low density polyethylene/thermoplasic sago starch plastic (PES), hydro-biodegradable polylactic acid plastic (PLA), or oxo-biodegradable plastic (OXO). There were no differences in most nutrient contents of beef patties after storage nor the level of lipid oxidation when packed with the biodegradable compared to the non-biodegradable films. Beef patties packed with biodegradable packaging materials were able to retain moisture without jeopardizing the diameter reduction during

storage.

Biodegradable films with antioxidant properties based on Ecoflex1 and Ecoflex1-polylactic acid (PLA) containing a-tocopherol and olive leaf extract were developed by Marcos et al. (2014) using blown film extrusion. There was a good recovery of tocopherol from Ecoflex films (98–112%). Oleuropein and oleuroside were the main antioxidants detected in the olive leaf extract. A reduction of oleuropein content (21–33%) and an increase of oleuroside (14–31%) were observed and the films containing tocopherol exhibited higher antioxidant activity than the films containing olive leaf extract.

Muppall et al. (2014) prepared films with carboxymethyl cellulose (CMC), polyvinyl alcohol (PVOH) and clove oil in different ratios. Addition of PVOH led to improvement in mechanical and gas permeability properties of the CMC films, whereas, water vapor transmission rate decreased. All the films had negligible oxygen transmission rate. Minced chicken meat packed in these films had lower total viable counts and displayed a shelf life of 12 days, whereas, control samples spoiled within 4 days during refrigerated storage. The efficacy of these films was also demonstrated by packed inoculum studies against S. aureus and B. cereus in the chicken meat.

Peelman et al. (2014) evaluated the shelf-life (4°C) of foods inclusing rump steak and ham sausage that were MAP-packed in PLA and cellulose-based multilayer packages and compared with those packed in conventional non-degradable materials. The bio-based packages showed sufficient gas barrier properties to guarantee the shelf-life of MAP-packed food products, even when materials with lower barrier properties were used. However, for rump steak and ham sausage, increased light permeabilities of the packaging materials led to more discoloration. The biobased materials also performed well on the industrial packaging machines, but too brittle to hold larger contents.

Biodegradable and biocompatible gelatine-laponite composite films were developed by Li et al. (2015) who evaluated its effect on the quality of fresh pork during storage at 4 oC for 9 days. The films exhibited substantial enhancement of meat quality by impeding lipid oxidation and protein decomposition during storage due to the oyygen barrier capability of laponite.

### 4.3.7 Patents in edible coatings/films for meat and meat products

By providing physical protection and serving as a semi-permeable barrier toward the gases and water vapor, as well as offering additional benefits such as antimicrobial and antioxidant functions, edible films and coatings have attracted great interest as systems to increase the storage life and help ensure the microbial safety of meat and meat products. The recent inventions in edible coatings and films for meat and meat products mainly focus on the utilization of various renewable sources as film and coating materials; improvement in film/coating formulations and integration of antimicrobial and antioxidant substances for making the films and coatings with appropriate barrier properties to CO2, O2, water, and oil; possess good mechanical strength, acceptable sensory characteristics, and microbial, biochemical and physicochemical stability. The following section summarises the recent inventions in this area.

**1). Edible films to replace traditional casing**

There have been several inventions of new edible films to replace traditional casing for sausages and other processed meat products. Macquarrie et al. (2004) prepared edible films incorporating carrageenan in conjunction with konjac and/or gellan gums as substitutes for edible collagen film currently used in meat processing. Compositions of the films can overcome the inherent thermoreversibility of carrageenan gel resulting in the films being stable to exposure to hot or boiling water. The films can be readily processed

to form casings, bags or other food packaging. Macquarrie (2005) further developed edible films incorporating carrageenan in conjunction with insoluble and inert carbohydrate components, such as high-amylose starch. Such films exhibit properties required for meat casings, including high strength and excellent adhesion to the meat. Liquid compositions for casting into such edible films can facilitate the efficient production of sausage and other film-encased meat products using conventional forming apparatus. Macquarrie (2012) recently invented tubular sausage casings prepared from non-animal materials, primarily starches and flours by film-casting followed by gluing with an edible adhesive composed of konjac and carrageenan. Again, the casing can be used with conventional sausage production technology.

Furthermore, Macquarrie (2014) also designed another sausage casing and wrapper for hams and other cured meat products by combining gelatin and other hydrocolloid film forming polymer materials. Edible film compositions are formed by solution casting which results in a film exhibiting desirable properties of adherence to the meat product and giving a shining and appealing appearance to the product surface. Liu and Zang (2012) also invented an edible soy protein casing film containing 40-45% soy protein, 25-30% collagen, 4-8% glycerol, 5-10% polyvinyl alcohol, 3-6% edible fibre, and 0.3-0.8% glutaraldehyde. This soy protein casing has high tensile strength, high elongation, steam resistance, good product quality, and meets the requirements of stuffing sausages in various flavours.

## 2). Edible films and coatings integrating antimicrobials and antioxidants

Hettiarachchy and Stachithanadam (2005) provided an edible film solution incorporating organic acids, protein and glycerol for coating meat and other food items. These edible films can inhibit pathogen growth including L. monocytogens, S. gaminara and E. coli 0157:H7. Kaplan and Singh (2007) prepared free radical scavenging polymers with antioxidant functions. The films can increase shelf-life and quality of oxygen sensitive food when used as packaging or as coatings. A potato starch based film containing a starch swelling inhibitor, a nucleophile, an alkaline solution, a crosslinking agent and water, and phosphorus oxychloride was designed by Huang and Zhou (2013).. This film is inexpensive, and suitable for packaging meat and other products. Lin et al. (2013) developed an edible composite preservative film applied to preservation of fresh pork in a supermarket. The film contains 1% lactic acid, 1% ascorbic acid, 0.25% nisin, 0.5% chitosan, 1% sodium alginate, and 1% glycerol, a pH of 3.5-4.0. This film can prolong the shelf-life of the fresh pork, packaged on a supermarket tray stored at 5-8 oC, from 1-3 days to over 7 days,.

Su et al. (2013) developed an antibacterial edible coating for preservation of bacon. The coating is formed from sodium carboxymethyl cellulose and gelatin with added glycerol as a plasticizer, sucrose ester as a hydrophobic agent, and potassium sorbate as a preservative. The coating can effectively extend the shelf-life of bacon. Zhou et al. (2013) prepared a chitosan-based composite preservative film or coating that has antibacterial, antioxidant and moisture resistance functions, and can be used for packaging or coating meat and other food products for prolonging product shelf-life. An antibacterial coating along with ultra-high pressure processing technology for conventional pickled bacon products was invented by Huang et al. (2013).This film can control the growth of putrefying bacteria and pathogenic bacteria, and prolong shelf-life. Sodium alginate is the coating material, and tea polyphenol is added as a preservative.

The film is prepared through a calcium salt cross-linking process, so as to take effects of the sterilizing and preventing the bacterium propagation. This technology can prevent oxidation stain on the meat surface, which is a shortcoming of sodium alginate coating. Stolzenhoff (2014) designed a method for producing a new meat product, in which an edible film is imprinted with food coloring and the imprinted film is applied

to raw meat, which is then cooked. Zhao et al. (2014) invented a nano-cellulose based edible coating and film technology integrated with other functional substances, such as antimicrobials and antioxidants to extend shelf life and ensure safety of meat and other food products.

## 4.4 Nanotechnology in meat packaging

Nanotechnology involves the application of materials with at least one dimension of less than 100 nm. Particulates, platelets and fibers are the 3 main classes of nanomaterials (Thostenson, Li, & Chou, 2005). Because of their nanoscale dimensions, these materials have proportionally larger surface area and consequently more surface atoms than their microscale counterpart. When added to compatible polymers, the nanomaterials can dramatically enhance the material properties of the nanocomposites, including improved mechanical strength, enhanced thermal stability and increased electrical conductivity (Uskokovic 2007). Thus, applications of nanomaterials in food and meat packaging are promising for improving mechanical properties, barrier properties, and/or conferring the packaging with new functionalities such as antimicrobial and antioxidant activity, biodegradability and intelligence ability (Bradley, Castle & Chaudhry, 2011), as well as ability to withstand the stress of thermal food processing, transportation, and storage (Sinha, & Okamoto, 2003; Thostenson, Li, & Chou, 2005).

In a survey in New Zealand on public acceptance of nanotechnology in lamb and beef processing (Cook, & Fairweather, 2007), a larger proportion (77%) of consumers expressed the intention to purchase the product, compared to the intention to purchase genetically modified (GM) food in general (10%) (Cook et al., 2002) and GM tomatoes in particular (28%) (Gamble et al., 2000). These preliminary findings suggest a high consumer acceptance of nanotechnology in meat industry, though more surveys are required to confirm this. In the food packaging sector, nanocomposites are commonly mixtures of polymers with inorganic or organic nanomaterials, typically 1-7 % of modified nanoclays (Lagaron et al., 2005). Some examples of synthetic and natural polymer based nanocomposites, levels of incorporation, methods of processing and the enhanced material properties of these materials are presented in Table 14.

### 4.4.1 Silver nanoparticle packaging

Silver nanoparticle (Ag-NP) is an anti-fungal and anti-microbial agent with high temperature stability and low volatility and has been claimed to be effective against 150 different bacteria types (Kumar & Munstedt, 2005). The antimicrobial property of Ag-NP may arise from its adhesion to the bacterial cell surface, leading to degradation of membrane lipopolysaccharides resulting in the formation of "pits" in the membranes and hence their malfunction (Sondi & Salopek-Sondi, 2004). The nanoparticles may also penetrate into the bacterial cell, damaging DNA, and may release antimicrobial Ag+ ions which bind to molecular electron donor groups in the cell and cause microbe death (Morones, et al., 2005).

A typical method for preparation of Ag-NP is chemical reduction of Ag+ in aqueous solution to produce colloidal silver with particle diameters of several nanometers (Wiley, Sun, Mayers, & Xia, 2005). This process is often performed in the presence of stabilizers to avoid undesirable agglomeration of colloids, which may lower the antibacterial activity (Sharma, Yngard, & Lin, 2009). Smaller Ag-NPs with larger surface area generally possess better bactericidal efficacy than larger Ag particles (An, Zhang, Wang, & Tang, 2008), and nanocomposites with a low silver content (0.06 wt%) in a polyamide 6 based film had higher efficacy against E. coli than microcomposites with a much higher silver content (1.9 wt%) (Damm, Munstedt, & Rosch, 2008). The thermal stability, modulus and strength of a polyvinyl alcohol (PVOH) matrix were also improved after incorporation of Ag-NP (Mbhele et al. 2003).

Commercial utilization of silver nanoparticles in plastic food containers has been reported by several companies such as Sharper Image® and Blue Moon Goods in the USA, Quan Zhou Hu Zeng Nano Technology in China, and A-DO Global in South Korea (Silvestre, Duraccio, & Cimmino, 2011). Anti-bacterial and anti-microbial properties have been claimed for these packaging materials allowing the packaged and stored food to be safer, fresher, healthier and tastier. Absorbent pads are commonly used in retail meat packaging to absorb water and fluids (drip) exuded from meat and meat products, preserving the fresh appearance of the products and avoiding their contact with unsanitary juices (de Azeredo, 2013). However, these juices absorbed in the pads may favor growth of spoilage and pathogenic bacteria. Incorporation of Ag-NP in porous cellulose fibre (He, Kunitake & Nakao, 2003) can be used as an antimicrobial pad for meat packaging. For example, the microbial loads (total viable counts, lactic acid bacteria) in the drip were 90% lower than the controls when the Ag nanoparticle-adsorbed cellulose fibers were used as absorbent pads to pack minimally processed meat products (Lloret, Picouet, and Fernández, 2012). These cellulose-Ag hybrid materials also reduced the levels of the major microbial groups (total aerobic bacteria, lactic acid bacteria, Pseudomonas spp., and Enterobacteriaceae) in the absorbent pads of the modified atmosphere packaged beef meat (Fernández, Picouet, and Lloret, 2010).

**Table 14. Some examples of synthetic and natural polymer based nanocomposites, levels of incorporation, methods of processing and their enhanced material properties (modified from Mihindukulasuriya & Lim, 2014).**

| Polymer | Nanomaterial | Level of incorporation | Method of processing | Enhanced material properties |
|---|---|---|---|---|
| Poly(vinyl alcohol) (PVA) | Cellulose nanocrystals (CNC) | 1-5% dry basis (wt) | Solvent casting | Increased tensile strength (TS) |
| Poly(e-caprolactone) (PCL) | CNC | 0-12% (wt) | Film casting | Decreased water vapor permeability (WVP) |
| Low-density polyethylene (LDPE)/Linear low-density polyethylene (LLDPE) | Nanoclay | 0-50% (wt) | Co-rotating twin-screw extrusion | Enhanced elastic modulus (EM) |
| Polyethylene (PE) | Layered silicate | 5-15% (wt) | Micro-extrusion | Increased crystallization temperature |
| Polypropylene (PP)/ Ethylene propylene diene rubber (EPDM) blend | Montmorillonite (MMT) based organoclay | 3-7% (wt) | Melt extrusion | Increased $O_2$ and $CO_2$ barrier properties |
| Maleated PE | Silicate | 15% (wt) | Melt extrusion | Increased film stiffness |
| Poly(ethylene-co-vinyl acetate) (EVA) | Nanosilica | 1-9 parts per hundred polymer | Two-roll mixing | Increased TS, hardness, and abrasion resistance |
| Soy protein isolate | MMT | 5-15% | Melt extrusion | Increased TS and decreased WVP |
| Poly(lactic acid) (PLA) | CNC and silver (Ag) nanoparticles | 5% CNC & 1% Ag nanoparticles | Solvent casting | Reduced oxygen transmission rate (OTR) and WVP |
| Starch | Silicon carbide (SiC) | 0-10% | Solution technique | Decreased oxygen permeability (OP) |
| Sago starch and bovine gelatin | Zinc oxide nanorods (ZnO) | 1-5% | Solvent casting | Decreased OP and increased mechanical and heat seal properties |

| Polyhydroxybutyrate-co-valerate (PHBV), polycaprolactone (PCL), PLA* | Mica nanoclay | 5% (wt) | Film casting | Enhanced barrier properties to UV light, oxygen, water, and limonene |
| Chitosan ** | Ag-zeolite | 2.1-2.8% | Solvent casting | Enhanced antimicrobial activity against both Gram-positive and Gram-negative bacteria |

\* Sanchez-Garcia, & Lagaron, 2010.
\*\* Rhim, Hong, Park, & Ng, 2006.

### 4.4.2 Metal oxide nanoparticle packaging

Metal oxide materials such as titanium dioxide (TiO2), zinc oxide (ZnO) and magnesium oxide (MgO) possess antibacterial activities mainly because they generate reactive oxygen species that can damage microbial cell DNA (Premanathan, Karthikeyan, Jeyasubramanian, & Manivannan, 2011). One benefit of utilization of metal oxides over organic antimicrobial agents is their higher stability (de Azeredo, 2013). In addition, metal oxide nanaomaterials have other properties including UV-blocking, and ethylene or oxygen scavenging activities (Llorens, Lloret, Picouet, Trbojevich, and Fernandez, 2012). To synthesize the metal oxide nanoparticles, the sol-gel method has been frequently used and the nanoparticle properties are determined by the nucleation, growth, and aging mechanisms (Oskam, 2006).

For food packaging applications, TiO2 nanoparticles have been incorporated into oriented polypropylene (OPP) (Chawengkijwanich and Hayata, 2008) or a mixture of polyethylene (PE), polyethylene wax, octadecanoic acid, and petroxolin (Xing et al., 2012) to make antimicrobial films. Other metal oxide nanoparticle films, such as polyvinyl chloride (PVC) nanocomposites with modified Ag-TiO2 nanoparticles (Cheng et al, 2006), nano-ZnO / LDPE films (Emamifar et al., 2010), nano-ZnO/starch-coated polyethylene (SCP) (Tankhiwale and Bajpai, 2012) and nanosized ZnO/SnO2 thin films (Talebian, Nilforoushan, and Zargar, 2011) have been reported for food packaging. These films have a wide spectra of antimicrobial activities against both Gram positive and negative microorganisms, and have a great potential to be used in meat packaging. Commercially, nanoparticles of silver zeolite from Sinanen Zeomic Co. Ltd. (Nagoya, Japan) and Agion Technologies (Wakefield, MA, USA) have been used in development of active packaging films and have FDA (Food and Drug Administration and EFSA (European Food Safety Authority) approval for food contact use (Silvestre, Duraccio, & Cimmino, 2011).

### 4.4.3 Nanoclay packaging

Polymers incorporating clay nanoparticles were among the first polymer nanomaterials for food packaging. Several different polymers and clay fillers can be used for obtaining clay–polymer nanomaterials and the most used polymers are polyamide, nylon, polyolefins, polystyrene, ethylene–vinylacetate copolymer, epoxy resins polyurethane, polyimides and polyethylene terephthalate (Silvestre, Duraccio, & Cimmino, 2011). A widely available natural and relatively cheap nanoclay is montmorillonite (MMT), which is a hydrated alumina-silicate layered clay consisting of aluminium hydroxide between silica layers (Paiva, Morales, & Diaz, 2008). Modified MMT has been obtained by substituting inorganic cations of MMT with organic ammonium ions to achieve a more homogeneous distribution of clay in the matrix, and consequently substantial improvements in the gas and water barrier properties of the composite (Koh et al., 2008; Bharadwaj, 2001). The improved barrier properties of polymer–clay nanocomposites are probably due to the complex and long path around the clay layers required for gas and water to diffuse through the film (Nielsen 1967).

For example, thin films of sodium montmorillonite clay and branched polyethylenimine were deposited on various substrates using layer-by-layer assembly to obtain a transparent clay–polymer material with an oxygen barrier at almost 100% (Priolo, Gamboa & Grunlan, 2010). Clays have also been reported to improve mechanical properties, thermal stability and resistance to fire of polymers such as polyethylene, polypropylene, nylon, poly(e-caprolactone) and polyethylene terephthalate (PET. (Weiss, Takhistov & McClements, 2006; Park et al., 2003; Silvestre, Duraccio, & Cimmino, 2011). UV blocking properties were achieved in mica nanocaly incorporating biopolymers of poly(lactic acid) (PLA), polyhydroxybutyrate-co-valerate (PHBV), and polycaprolactone (PCL) (Sanchez-Garcia & Lagaron, 2010). This property is in great demand for packaging light sensitive foods including some meat products. Moreover, the addition of low amounts of nanoclay does not compromise the inherently useful properties of the base polymer matrixes such as transparency, toughness and flexibility (Marras, Kladi, Tsivintzelis, Zuburtikudis, & Panayiotou, 2008; Sanchez- Garcia, Lagaron, & Hoa, 2010). Therefore, the nanoclay films have a potential to be used as a transparent gas and UV barrier film for meat packaging.

According to Moraru et al. (2003), some companies such as Nanocor Inc. (Arlington Heights, IL, USA) and Southern Clay Products, Inc. (Gonzales, TX, USA) have been working on commercialisation of nanocomposites incorporatingd MMT to make lighter, stronger, more heat-resistant plastics with improved barrier properties against gases and moisture. Nylon-6 incorporating clays resulting in improved barrier properties have also been marketed (Brody 2007). Another commercial nanomaterial, nylon MXD 6 or Imperm ®, has been developed by Nanocor and Mitsubishi Gas Chemical (New York, NY, USA) with much improved barrier properties for use in films and PET bottles (Brody 2006; 2007). In addition, the US Army Natick Soldier Center (Natick, MA, USA) has incorporated nanoclay into plastic matrices (eg. PE, PET) to improve barrier properties, thermal resistance, and mechanical strength of packaging materials. This has resulted in enhanced shelf life of room-temperature shelf-stable foods, reduced solid waste from package materials, and allows fast reheating in microwave ovens (Brody 2006). These nanoclay–polymer nanomaterials have a promising future for use in a wide variety of food packaging applications including meat and meat products.

### 4.4.4 Other nanomaterial packaging

Chitosan is a linear polysaccharide consisting of randomly distributed β-(1-4)-linked D-glucosamine (deacetylated unit) and N-acetyl-D-glucosamine (acetylated unit), which is made by hydrolysis of shrimp and other crustacean shells with the alkali, sodium hydroxide. Chitosan nanoparticles (CSNP) are usually prepared by electrostatic interaction between positively charged amine groups of chitosan and the negatively charged groups of a polyanion (e.g. tripolyphosphate (TPP)) under specific pH conditions (Zhao et al., 2011). Although chitosan has been reported as an antimicrobial agent against a wide variety of microorganisms (Wu, Zivanovic, Draughon, Conway, & Sams, 2005), CSNP and its derivatives have greater antibacterial activity than chitosan itself because of their higher surface area and charge density (Qi, Xu, Jiang, Hu, & Zou, 2004). CSNP can be incorporated in biopolymers and has been developed into edible or biodegradable antimicrobial food packaging materials. For example, Watthanaphanit et al. (2010) prepared alginate/chitosan nanocomposite yarns by mixing a chitosan whisker colloidal suspension with a sodium alginate solution, followed by extrusion into fibers by wet spinning. The alginate/chitosan nanocomposite yarns imparted antibacterial activity against both Gram-positive S. aureus and Gram-negative E. coli. Other CSNP composites, such as silver loaded chitosan nanoparticles (Ag–CSNP) (Ali, Rajendran, and Joshi, 2011), chitosan–clay nanocomposite films (Rhim, Hong, Park, and Ng, 2006), and chitosane–ZnO nanofibres (Wang, Zhang, Zhang, and Li, 2012), all demonstrated excellent antimicrobial activities, which have high potential to be used for meat packaging materials.

Cellulose is a natural plant cell wall polymer. Generally two types of nanomaterials – microfibrils and whiskers, can be obtained from cellulose. The microfibrils have nanometre scale diameters (2–20 nm) and micrometre scale lengths (Azizi Samir et al., 2005; Oksman, Mathew, Bondeson, & Kvien, 2006), whereas the whiskers have the diameters of about 8–20 nm or less and lengths ranging from 500 nm up to 1–2 μm (Azizi Samir et al., 2004; Lima & Borsali, 2004). To prepare the cellulose nanowhiskers, the native microfibers or microfibrilated cellulose are treated with strong acids such as sulfuric acid (Petersson, Kvien & Oksman, 2007). Cellulose nanomaterials have been considered as low cost, lightweight, and high-strength nanocomposites to develop food packaging films with improved properties (Podsiadlo et al., 2005). For instance, a poly(styrene-co-butyl acrylate) latex film containing 30 wt.% of straw cellulose whiskers exibited a modulus more than a thousand times higher than that of the bulk matrix (Helbert et al., 1996). The thermal stability of poly(lactic acid)  (Petersson et al., 2007) and poly(styrene-co-butyl acrylate) latex film (Helbert et al., 1996) were also improved when cellulose whiskers were added. Furthermore, the moisture barrier of polymer films has been enhanced by incorporation of cellulose nanomaterials (Paralikar, Simonsen, & Lombardi, 2008; Sanchez-Garcia, Gimenez, & Lagaron, 2008). The lower moisture permeability of the cellulose nanomaterial-enforced films may be as a result of the increased tortuosity in the materials leading to slower diffusion processes (Sanchez- Garcia et al., 2008). The barrier properties of these nanocomposite films are further enhanced if the cellulose nano-filler is less permeable, and have good dispersion in the matrix with a high aspect ratio (Lagaron, Catala, & Gavara, 2004).

Other type of nanoparticles that have been incorporated into biopolymers for tailoring their properties are carbon nanotubes (CNT) and/or carbon nanofibers (CNF). The major purposes of adding this type of nanoparticle into biopolymers is to increase their biodegradation rate, enhance mechanical properties, increase thermal and electrical conductivity (Chen & Wu, 2007; Sanchez-Garcia, Lopez-Rubio, and Lagaron, 2010), and improve gas and water vapour barrier properties (Sanchez-Garcia, Lagaron & Hoa, 2010). Therefore, the CNTs have the potential to be used in food packaging applications, such as microwavable packaging and intelligent packaging designs, due to their good electrical and thermal conductivity. However, the issues of a strong black colour and the potential toxicity of CNTs should be seriously considered before they are used for food packaging (Sanchez-Garcia, Lagaron & Hoa, 2010).

### 4.4.5   Patents on nanotechnology in meat packaging

Recently, many patents on nanotechnology in meat packaging have been published. These include: development of novel antimicrobial films or coatings using different nanoparticles including formulations containing nano silver and doped metal oxides (Yadav & Vecoven, 2005), adding 0.5-2% nano-TiO in PE or PS plastics (Yang et al. 2005), or spraying nanofiber solutions (composed of catechin, copper nitrate and polyvinylpyrrolidone) onto the surface of pork to extend its shelf life (Chen, Li, Zhao, & O, 2014).  An antimicrobial absorbent pad was invented by Durdag et al. (2013) which can be placed under the meat on the packaging tray to absorb the exudate liquid and destroy contact microbes. The pad contains non-woven biodegradable thermoplastic polymers (e.g. PA, PLA) as the support material and nano silver, silver-based or silver ion-based chemicals as antimicrobial agents.

To improve meat packaging film properties, Zhu (2005) invented a multilayered film using nanoclay, nano SiO2, TiO2, CaCO3 as the barrier layer. The film was biodegradable and had good transparency, gas barrier properties, heat sealability, printability, as well as resistance to high temperature cooking. Daponte & Janssens (2005) prepared a packaging film comprising polyolefin and nano zinc oxide with a particle size between 1 and 100 nm. The film had a high transparency for visible light but was UV opaque and thus

could be used as a UV barrier material to protect meat against colour change. Koenig et al. (2008) developed a food casing based on cellulose hydrate that included nanoclay, nano TiO2, and nano silver, with the nanoparticles measuring from 0.5 to 1000 nm. This material could be an ideal synthetic sausage casing because it has the advantages of high mechanical strength; good elastic shrinkage behavior (so that it does not separate from the food even after prolonged storage); resistance to hot or boiling water; resistance to cellulytic enzymes that form from edible molds under unfavorable conditions; and has bacteriocidal action. To increase the gas transmission rate, Grah (2011) developed a packaging film comprising at least 0.001 weight % of fullerene material selected from spherical fullerenes, bowl-shaped fullerenes, multi-walled carbon nanotubes, carbon nanocones, and carbon nano-onions. The oxygen transmission rate of the packaging film could be about 100 cc (STP)/m2·day (1 atm, 0% RH, 23 °C). This packaging is of value for fresh meat retail packaging, since it allows oxygen from ambient air to reach the interior of the package allowing the meat to "bloom" to a red color suitable for retail display.

### 4.4.6  Safety consideration of nanomaterial packaging

Application of nanomaterials in food packaging can lead to lower weight packages because less material is needed to obtain the same or even better barrier properties, which in turn can lead to reduced package cost with less packaging waste (Rhim, Park, and Ha, 2013). In addition, nanomaterials can potentially meet many of the meat industry's needs in relation to innovative, strong, lightweight, active and intelligent food packaging (Smolander & Chaudhry, 2010). However, there are two key issues of the application of nanomaterial and nanotechnology in food packaging: safety to consumers and impact on the environment.

The safety issue is mainly focussed on whether the nanomaterial in food packaging may migrate into the food and have negative impact on the safety or the quality of the food (EFSA 2009). If this migration happens, the consequence of ingesting these nanoparticles within the gastrointestinal tract is not known. Little is inderstood of how these particles will act when they enter the body, how and if they are absorbed by different organs, how the body might metabolise and eliminate/excrete (Silvestre, Duraccio, & Cimmino, 2011; Rhim, Park, & Ha, 2013). Compared with macroparticles, the unique chemical and physical properties of nanoparticles may result in completely different toxicity profiles and mechanisms. This highlights the need for risk assessment on nanoparticles on a case-by-case basis (Munro, Haighton, Lynch, & Tafazoli, 2009). Currently, there is a lack of understanding of how to evaluate the potential hazard of nanomaterials by the oral (food) route and there is a lack of tools to estimate the potential migration of nanomaterials from packaging into food.

The environmental concern of nanomaterial packaging focusses on its potential for negative impact on the environment during its production and disposal (Bradley, Castle & Chaudhry, 2011). It is not known if the nanomaterials will interact with environmental substances and/or themselves transform to other chemicals with modified nano-related chemical, physical and toxicological properties. However, it has been reported that nanoclays in biodegradable matrices do not delay biodegradation during composting. Due to their inherent high surface energy, nanoclays re-attach to each other to become microparticles of soil once the polymer matrix disappears (Lagaron & Fendler, 2009).

Several other studies have also demonstrated that addition of nanoclays to various synthetic polymers led to enhanced or accelerated degradation in comparison with the kinetics observed for the base polymers (Kumanayaka, Parthasarathy, & Jollands, 2010; Qin, Zhao, Zhang, Chen, & Yang, 2003). Therefore, nanocomposites containing nanoclays could be regarded as more environmentally friendly materials even when the matrix is a synthetic polymer (Lagaron & Lopez-Rubio, 2011). More research

needs to be done to understand the potential risks of nanomaterials and more evidence-based information should be provided to the regulatory authorities (e.g. EFSA, FSANZ and US-FDA) before approval of new nanomaterials for use in food packaging.

## 5.0 Regulatory aspects of meat packaging

Packaging materials may directly contact with the meat surface and packaging technology can affect food safety and quality of meat products, which consequently could affect consumer health. In light of this, almost all governments and some organisations (such as Food and Agricultural Organization (FAO), World Health Organization (WHO)) have a series of regulations and/or national/international standards to guide how to safely use packaging materials and technologies. This section of the review presents a brief summary of the major regulations for meat packaging.

### 5.1 USA

#### 5.1.1 US regulation on meat packaging materials

U.S. Food and Drug Administration (FDA) approve all food packaging materials. Any material intended for use in food packaging must be formulated in compliance with FDA requirements for its intended use. The manufacturer of a new material, if not already regulated, must petition FDA and provide data clearly demonstrating that the material is safe for its proposed use.

Meat and poultry products may not be packaged in a container composed of any substances that may adulterate the contents or be injurious to health. Packaging materials entering a meat or poultry plant must be accompanied by or covered by a guarantee or statement of assurance from the packaging supplier. The guarantee must state that the material complies with the Federal Food, Drug and Cosmetic Act. It must also state the brand name, supplier, and conditions for use, including temperature and other limits.

USDA's Food Safety and Inspection Service (FSIS) monitor the use of packaging material in all meat and poultry processing plants. The processing plants must maintain a file containing guarantees for all packaging materials used within the plant. This file must be open to FSIS officials at all times. To verify guarantees, FSIS randomly selects packaging materials for review. If the agency determines a packaging material does not comply with Federal food laws and regulations, the material is disapproved and its use in federally-inspected meat and poultry plants may be denied. Inspectors may question a packaging material's performance or other physical aspects.

#### 5.1.2 US meat packaging label regulation

A guide to federal food labeling requirements for meat, poultry, and egg products can be found at: http://www.fsis.usda.gov/shared/PDF/Labeling_Requirements_Guide.pdf and detailed information about "Meat and Poultry Labeling" can be found at the USDA FSIS website at http://www.fsis.usda.gov/wps/wcm/connect/e2853601-3edb-45d3-90dc-1bef17b7f277/Meat_and_Poultry_Labeling_Terms.pdf?MOD=AJPERES

Under USDA regulations, meat packaging labels must include the following information (http://www.ct.gov/doag/lib/doag/marketing_files/15._meat_4-15-2010.pdf):

- Species, primal source and standard descriptive term (retail name)

- Name of packaging firm

- Address of packaging firm

- Net weight

- Price per pound

- Total package price

- Whether the product is boneless or bone-in

- Safe handling label

- List of all ingredients for multi-ingredient products such as sausage

- Species and primal source or area if not a multi-ingredient product as follows:

    o Beef: cheeks, tongue, gullets or esophagus, shoulder, chuck, heart, brisket, shank, shin, rib, plate, diaphragm, loin, flank, rump, top round or bottom round

    o Veal: cheeks, tongue, gullets or esophagus, heart, neck, shank, breast, shoulder, rib, loin, sirloin, rump or leg

    o Lamb: cheeks, tongue, gullets or esophagus, heart, neck, shank, breast, shoulder, rib, loin or leg

    o Pork: cheeks, tongue, gullets or esophagus, heart, tail, jowl, shoulder, shoulder picnic, shoulder butt, feet, side, spareribs, loin, loin-shoulder end or loin-rib end, loin-center cut, loin-loin end, fat back or ham

### 5.1.3 US Regulation on active and intelligent packaging

In the US, the term "active packaging" generally describes any packaging system that protects food from contamination or degradation by creating a barrier to outside conditions while interacting with the internal environment to control the atmosphere within the package. Intelligent packaging materials have no effect on the food, but are designed to convey information about the condition of the food to the consumers (Ettinger, 2002).

Ettinger (2002) and Keller and Heckman (2002) have presented full details of the US regulations on active and intelligent packaging. Some of the important information is now summarised. All food contact substances must comply with the Federal Food, Drug, and Cosmetic Act. A substance that meets the Act's "food additive" definition will be considered "unsafe" unless it is used in accordance with an applicable food additive regulation or an effective food contact notification. A "food additive" is defined in Section 201(s) of the Act as a substance that is reasonably expected to become a component of food under the intended conditions of use. Food additives that result from incidental exposure from a package may be referred to as indirect food additives (i.e., those not added directly to the food). Statutory exemptions from the "food additive" definition are provided for substances that are "generally recognized as safe (GRAS)" or are used in accordance with a sanction or approval issued prior to the enactment of the Food Additives Amendment of 1958. Some food contact substances have received specific exemptions from FDA on a case-by-case basis under the "Threshold of Regulation" rule. Food that contains an "unsafe" food additive is deemed adulterated under Section 402(a)(2)(C) of the Act (Ettinger, 2002; Keller and Heckman, 2002).

For chemicals or scavengers added to packaging for reducing spoilage rate or to maintain some characteristics of the food, the Code of Federal Regulations (CFR) anticipates that they have physical and technical effects on food contact articles (21 CFR Part 174.5 ("General provisions applicable to indirect

food additives")). The regulation specifies that these additives shall not exceed, where no limitations are specified, amounts required to accomplish the intended physical or technical effect in the food-contact article.

As long as the material in the active or intelligent packaging system is intended neither to add any substance to the food, nor to have a technical effect in the food (so-called "indirect additives"), there are no special regulatory concerns for substances that are used in such systems. Hence, they are simply regulated like all other food contact substances. If, on the other hand, the active packaging material is added directly to food, or has a technical effect in the food, the material would constitute a "direct additive" and would be subject to much stricter FDA regulatory requirements (most likely, a food additive petition would have to be filed with FDA unless another exemption could be claimed) (Ettinger, 2002).

While no additional regulatory concerns exist for additives used in active packaging, it is important that manufacturers account for any additional migrants, decomposition by-products, or impurities that may occur as a result of the chemical activity in the active packaging material during its storage and shelf-life. This information is needed before it can be assessed whether the material in the active packaging system constitutes a "food additive." It cannot be determined whether a substance is reasonably expected to become a component of food under the intended conditions of use, nor can it be calculated whether the dietary exposure to a substance used or created in the active packaging system might occur, unless any substances that may be produced and may enter the food is directly analyzed and quantified. Accordingly, residual and migration testing in active packaging systems must take into account the possible formation of these additional migrants and decomposition byproducts. FDA's guidelines for migration studies are available on the Agency's website (Ettinger, 2002).

More information about the US regulation of active and intelligent packaging can be found from Ettinger (2002) and Keller and Heckman (2002).

### 5.1.4 US federal regulations for edible coatings and films

According to the US regulations for "Food additives permitted for direct addition to food for human consumption", 21 CFR172, subpart C" (FDA, 2006), edible films and coatings can be classified as food products, food ingredients, food additives, food contact substances, or food packaging materials. Because they are an integral part of the edible portion of food products, any compound to be included in the formulation should abide by all regulations required for food ingredients, i.e., should be GRAS or regulated as food additive, and used within specified limitations. To maintain edibility, all film-forming components, as well as any functional additives in the film-forming materials, should be food-grade and non-toxic, and all process facilities should meet high standards for ensuring food safety (Rojas-Graü et al., 2009).

Chemical substances added as antimicrobials are regarded as food additives if the primary purpose of the substances is shelf-life extension. According to US regulations, organic acids including acetic, lactic, citric, malic, propionic, tartaric and their salts are GRAS for miscellaneous and general purpose usage. Many essential oils are also classified as GRAS substances or permitted as food additives (Rojas-Graü et al., 2009).

Another important issue pertinent to the regulatory status of edible coatings and films is the presence of allergens. Many edible films and coatings are made from allergic substances, such as milk, soy and wheat proteins or shellfish derivatives (chitosan). US regulation requires that the presence of a known allergen used within a coating must be clearly labelled (Franssen & Krochta, 2003).

### 5.1.5 US federal regulations for bioplastics

In the United States, the Federal Trade Commission controls environmental claims through the US Code of Federal Regulations (CFR) section 16, part 260 (16 CFR 260) – Guides for the Use of Environmental Marketing Claims (http://plasticsandtheplanet.com/archives/195).

From the regulation section 260.7,

(b) Degradable/biodegradable/photodegradable: It is deceptive to misrepresent, directly or by implication, that a product or package is degradable, biodegradable or photodegradable. An unqualified claim that a product or package is degradable, biodegradable or photodegradable should be substantiated by competent and reliable scientific evidence that the entire product or package will completely break down and return to nature, i.e., decompose into elements found in nature within a reasonably short period of time after customary disposal.

Claims of degradability, biodegradability or photodegradability should be qualified to the extent necessary to avoid consumer deception about: (1) the product or package's ability to degrade in the environment where it is customarily disposed; and (2) the rate and extent of degradation.

In order to substantiate their environmental claims, companies must test using standard measurement methods. Some organizations that have biodegradability testing methods are American Society for Testing and Materials International (ASTM), International Organization for Standardization (ISO), Organization for Economic Co-operation and Development (OECD), and U.S. Environmental Protection Agency (EPA).

Additional information on the regulations and testing methods for biodegradability of polymers can be found from Müller (2003) and McDonald (2013).

### 5.1.6 US federal regulation of nanomaterials in food

In the United States, FDA has not established regulatory definitions of "nanotechnology," "nanomaterial," "nanoscale," or other related terms. These terms however are commonly used in relation to the engineering of materials that have at least one dimension in the size range of approximately 1 nanometers (nm) to 100 nm.

In July, 2014, the FDA issued a final guidance entitled "Assessing the Effects of Significant Manufacturing Process Changes, Including Emerging Technologies, on the Safety and Regulatory Status of Food Ingredients and Food Contact Substances, Including Food Ingredients that are Color Additives". The summary of the guideline can be found at The National Law Review website (http://www.natlawreview.com/article/nanotechnology-food-production-fda-finalizes-guidance-manufacturing-process-changes-) (NLR, 2014).

This guidance identifies two Points to Consider that should be used to evaluate whether FDA regulated products involve the application of nanotechnology (FDA, 2014).
- Whether an engineered material or end product has at least one dimension in the nanoscale range (approximately 1 nm to 100 nm); or
- Whether a material or end product is engineered to exhibit properties or phenomena, including physical or chemical properties or biological effects that are attributable to its dimension(s), even if these dimensions fall outside the nanoscale range, up to one micrometer (1,000 nm).

These considerations apply not only to new products, but also when changes to manufacturing processes alter the dimensions, properties, or effects of an FDA regulated product or any of its constituent parts.

The two Points to Consider should be applied when considering whether an FDA regulated product involves the application of nanotechnology. An affirmative finding to either of the Points to Consider might suggest the need for particular attention to the product by FDA and/or industry for potential implications for safety, effectiveness, public health impact, or regulatory status of the product.

The guidance details the factors to be considered when evaluating changes in the manufacturing process for a food substance. Food substances include food ingredients, food contact substances and colour additives. FDA suggests that the reassessment of a food substance should be considered after making a "significant" change to the manufacturing process. FDA does not offer a clear definition for what constitutes a significant manufacturing process change, but notes that "[a]ny manufacturing change has the potential to be significant." FDA offers several examples (NLR, 2014):

- A change in one or more starting materials;
- A change in the concentration of starting materials;
- A change in catalyst;
- A change in the source microorganism (including a change in strain) used for a food substance derived from fermentation of a microorganism; and
- A change in food manufacturing or ingredient technology, such as the use of emerging technologies that affect the particle size distribution of a food substance.

The recommended factors for assessing significant manufacturing process changes are grouped into four categories based on the regulatory pathway for the food substance (NLR, 2014):

- Food substances, including food contact substances, that are the subject of a food additive or color additive regulation;
- Food contact substances for which there is an effective Food Contact Notification;
- Food substances that are affirmed or identified as GRAS in the Code of Federal Regulations; and
- Food substances (not including color additives) for which there is an existing determination that a use of a food substance is GRAS

Despite this grouping, the analytical process recommended by FDA is nearly identical, and involves (NLR, 2014):

- Determining what changes have been made to the identity of the food substance as a result of the change in manufacturing process, including its physicochemical structure and properties, purity, and impurities;
- Conduct a safety assessment for such changes to the food substance, including characteristic properties such as physicochemical structure and properties, purity, impurities, bioavailability, or toxicity;
- Consider whether the use of the food substance is within the existing regulatory authorization, taking into account changes to the identity of, manufacturing process for, or the conditions of use of the food substance, and any impurities introduced into the food substance by the change in manufacturing process;
- Consultation with FDA about such conclusions; and
- Making an appropriate regulatory submission to FDA as appropriate.

## 5.2    European Union

In Europe, the Framework Regulation (EC) No 1935/2004 is the general legislation that applies to all food contact materials (FCMs) including meat packaging materials. It sets out that FCMs shall be safe and not change the properties of food in unacceptable ways. Essentially, the European approach is based on the theory that all materials should be explicitly cleared and publicised in regulations, and that all clearances must be based on a toxicological evaluation of the listed substances (Restuccia, et al., 2010). This legislation sets out that materials and articles shall be manufactured in compliance with Good Manufacturing Practice (GMP) to protect the health of consumers by ensuring all FCMs (1) shall not endanger human health; (2) shall not change the composition of the food in an unacceptable way, and (3) not change the taste, odour or texture of the food.  It is noted that the Framework Regulation (EC) No 1935/2004 authorizes the use of active and intelligent packaging, provided the packaging can be shown to enhance the safety, quality and shelf-life of the packaged foods. The active and intelligent packaging materials shall not be used to adversely affect the organoleptic characteristics of foods or mask spoilage, and shall inform consumers that such packaging has been used for a specific food.

General requirements stated in Regulation 1935/2004/EC for the safe use of active and intelligent packaging have been recently integrated by EU Guidance to the Commission Regulation (EC) No 450/2009. The new Regulation also establishes specific requirements for the marketing of active and intelligent materials and articles intended to come into contact with food. It states that the substances responsible for the active and intelligent functions can either be contained in separate containers (e.g. oxygen absorbers in small sachets) or directly be incorporated in the packaging material (e.g. oxygen absorbing films) (Restuccia, et al., 2010). Furthermore, the materials may be composed of one or more layers or parts of different types of materials, e.g. plastics, paper, coatings and varnishes. In contrast with active packaging systems, intelligent packaging systems shall not release chemicals into the packaged food. Intelligent systems may be positioned on the outer surface of the package or be separated from the food by a barrier (functional barrier). The new regulation includes the provisions that active and intelligent materials and articles shall "be adequately labeled to indicate that the materials or articles are active and/or intelligent" but  "not give information about the condition of the food which could mislead consumers" nor lead to "masking the spoilage of food". The active substances in active and intelligent materials and articles to be released into the food or the environment surrounding the food shall "be authorised and used in accordance with the relevant EU provisions applicable to food". Therefore, these should undergo a safety assessment by European Food Safety Authority (EFSA) and the potential chemical release should "comply with any restrictions in the existing food law (e.g. as authorised food additives) thus complying with the safety requirement"

The use of plastic materials and articles intended to contact food in the EU is governed by Commission Regulation (EU) No. 10/2011. It includes a positive list of permissible monomers and other starting substances and additives. Only food-contact approved materials and additives should be used, and should do so below their corresponding threshold specific migration limits (SMLs). While the EU regulation establishes that SMLs may be adopted for 17 types of materials, at this stage specific measures exist for only a few materials (e.g. plastics, regenerated cellulose, active and intelligent materials) (FSANZ, 2014). Currently, some of the existing nano additives, such as those modified with ammonium salts do not comply with the current European food-contact directive issued by the EFSA (Commission Regulation (EU) No 10/2011).

## 5.3    Asia

### 5.3.1    China

In China, food and meat packaging is regulated by the Food Hygiene Law (http://www.gov.cn/banshi/2005-08/31/content_68767.htm, English edition http://wenku.baidu.com/view/8ee1d91052d380eb62946d88.html), Food Safety Law (http://www.gov.cn/banshi/2005-08/31/content_68767.htm, English edition http://wenku.baidu.com/view/bd02cc4fe518964bcf847ce6.html) and a series of National Standards. The main administration bodies for food quality and safety are China Food and Drug Administration (CFDA, http://eng.sfda.gov.cn/WS03/CL0755/), National Health and Family Planning Commission (NHFPC, http://en.nhfpc.gov.cn/about.html), Standardization Administration (http://www.sac.gov.cn/sacen/), and Ministry of Agriculture (http://english.agri.gov.cn/). The Food Hygiene Law sets out the general hygiene standards for food, food additives, food containers, food packaging materials, food utensils, equipment, detergents, disinfectants, as well as food business properties, facilities and environment. The Food Safety Law sets general rules on food risk monitoring and assessment, food safety standards, food production and operation, food examination, food export and import, food safety accidents, food safety supervision and management, and legal liabilities.

China's requirements for food packaging materials utilise a composite of both EU and US regulations. China National Standard GB 7718-2011 General Rules for Food Packaging Labelling (http://www.nhfpc.gov.cn/zhuzhan/zcjd/201402/544c0539b95d4d35b99ffbc105579071.shtml) deals with how the characters, figures, symbols and descriptions should be correctly used to provide the information on the packaged food to consumers, including name of the food, ingredients, net weight and size, manufacturers (name, location, contact information), production date and shelf life, storage conditions, food production permission numbers, product standard code and other legal required information. GB 9685-2008 Hygienic Standard for Use of Additives in Food Containers and Packaging Materials (http://www.nmwst.gov.cn/uploads/soft/sdsc/fj14814.pdf) specifies a positive list of more than 1500 permitted food contact additives, application scope, specific migration limits, maximum permitted quantity and other restrictions. The standard does not differentiate between whether the material comes in direct or indirect contact with food. Therefore some inks and adhesives used in food packaging not destined for primary packaging are also covered by this standard. Unapproved substances not on the positive list are not allowed unless a food contact notification has been submitted and approved by the CFDA, therefore any new materials such as active, intelligent and nano materials should also be submitted for CFDA approval before being used in food packaging. Many of the substances on the Chinese positive list are taken from the EU or USA regulations and share the same specific migration limits (SML).

### 5.3.2    Japan

In Japan, food contact materials are regulated by national legislation as well as by industry voluntary rules. The major national legislations for food, including meat packaging, are Food Sanitation Act (http://law.e-gov.go.jp/htmldata/S22/S22HO233.html), Ordinance for Enforcement of the Food Sanitation Act (http://law.e-gov.go.jp/htmldata/S23/S23F03601000023.html), Food Safety (Ministry of Health, Labour, and Welfare;  http://www.mhlw.go.jp/seisakunitsuite/bunya/kenkou_iryou/shokuhin/index.html), Food Additives (Standards and Evaluation Division, Food Safety Department, Pharmaceutical and Food Safety Bureau,                                                                                        MHLW; http://www.mhlw.go.jp/seisakunitsuite/bunya/kenkou_iryou/shokuhin/syokuten/index.html),    Positive

List System for Agricultural Chemical Residues in Foods (The Japan Food Chemical Research Foundation; http://www.ffcr.or.jp/Zaidan/FFCRHOME.nsf/pages/MRLs-n), JAS Law (Ministry of Agriculture, Forestry and Fisheries; http://www.maff.go.jp/j/jas/index.html), Food labeling & Japanese Agricultural Standard (http://www.maff.go.jp/e/jas/index.html), and Food Safety Committee (http://www.fsc.go.jp/index.html). Under the Food Sanitation Act, a food business operator shall take his/her own responsibility to ensure the safety of the food, additives, apparatuses or containers and packaging. In addition, he/she shall endeavour to obtain the knowledge and technologies necessary to ensure the safety of food for sale, conduct voluntary inspections of foods and take other necessary measures to ensure the safety of food for sale (Sumimoto, 2013). The legislation also outlines the rules under which chemical migration testing of hazards should be carried out in order to ensure that an article will meet the specification (Mori 2010). As such, metal cans, glass/ceramic/enamel articles, rubber and polymer articles have material-specific standards and are complemented by specifications on 15 particular resins (Mori 2010).

In Japan, some specific symbols are used to indicate that the packaged food product has met the JAS (Japanese Agricultural Standard) standards (Table 15).

Table 15. Specific symbols for packaged food products which have met the JAS (Japanese Agricultural Standard) standards (modified from Sumimoto, 2013)

| Name | Symbols | Features |
|------|---------|----------|
| JAS Mark |  | Foods and agricultural products that meet JAS standards (General JAS standards) in terms of quality, such as composition, grading, performance. |
| Specific JAS mark |  | Foods that meet the JAS standards of specific production or manufacturing method (specific JAS standards) or ones that meet the JAS standards for declaring distinctive features in quality. |
| Organic JAS mark |  | Food and agricultural products that meet the organic JAS standards can carry this mark on the packages. Agricultural products and foods processed from them with no organic JAS mark are not allowed to label "Organic." |
| JAS mark with production information |  | Beef and pork about which information on feeding and veterinary drugs are released; or processed foods about which information on ingredients and manufacturing processes etc. are released according the method that meets the JAS standards with production information can carry this mark. |

| JAS mark with a specific distribution method |  | Processed foods which are maintained at a specific temperature during distribution from manufacturing to marketing. Packed lunches using cooked rice including sushi and fried rice may obtain this certification. |
| --- | --- | --- |

Japan also has many voluntary industry standards which are sanctioned by specific well established trade associations (e.g. The Japan Hygienic Olefin and Styrene Plastics Association and the Japan Paper Association) (Ettinger, & Clark, 2015). Members of these associations (or sponsored companies) can apply for a voluntary standard for new substances as food contact materials. However, there is no specific legislation in Japan about the new active and intelligent agents as food packaging materials. All the new materials including nanomaterials intended to be used as food contact materials have first to be checked that they fulfil the national legislations or industry voluntary rules.

### 5.3.3 Australia and New Zealand

**1). Meat packaging labeling**

All cartons of Australian meat are labeled with information on the nature of the product and information allowing the product's full traceability. Carton labels include mandatory information required under Australian government regulation, and are consistent with the U.S. Department of Agriculture (USDA), the Canadian Food Inspection Agency (CFIA) and the Mexican Secretaria de Agricultura, Ganaderia, Desarrollo Rural, Pesca y Alimentacion (SAGARPA) requirements for labeling of imported meat products. In addition to mandatory information, Australian packers may include optional information on the label, allowing for further description for trade purposes. The following example (Figure 6) includes elements required to appear on labels for all Australian export beef cartons.



Figure 6. A label for Australian export beef cartons (http://www.australian-meat.com/Foodservice/Proteins/Beef/Labeling_of_Australian_Beef/)

1. Generic statement: Bone-in or boneless and identification of species.
2. Country of origin.
3. Carcass identification: Category code, which identifies the carcass age and sex.
4. Product identification: Primal cut description as shown in the Handbook of Australian Meat.
5. Primal weight range: Indicates that each primal cut in the carton is the minimum/maximum weight range as shown on the label.
6. Packaging type: Australian meat packaging code.

7. Barcode: Most developed and compliant with the GS1 (EAN.UCC) international meat industry guidelines.

8. Packed on date: Day, month, year and time the product was packed into the carton.

9. Best before date: End of the period for meat stored in accordance with any stated storage condition. Meat marked with "Best before date" can continue to be sold after that date provided that the meat is not damaged, deteriorated or perished. Meat marked with "Use by date" cannot be sold after that date.

10. Net weight: Meat content, less all packing material, shown to two decimal places in kilograms and pounds.

11. Batch number: In-house company identification number for product tracing when required.

12. Carton serial number: Individual identification number for carton.

13. Halal approved: Product has been ritually slaughtered and certified by an approved Islamic organization.

14. Establishment number: Plant-registered identification number.

15. AI stamp: Australia-government inspected.

16. Refrigeration statement: "Keep chilled/refrigerated" indicates the product in the carton has been held in a controlled chilled condition from the time of packing.

17. Number of pieces: Number of primal cuts in the carton.

18. Company code: In-house identification code for product in the carton.

For meat and meat product retail sale in Australia, other information such as price per kilogram and total package price, list of all ingredients and sometimes cooking methods are included.

## 2). Regulations for meat packaging materials

In Australia and New Zealand, the Food Standards Code developed and administrated by Food Standards Australia New Zealand (FSANZ) requires manufacturers to ensure food, including meat, that is in contact with packaging to be safe. For example, Standard 1.4.1 - Contaminants and Natural Toxicants (http://www.comlaw.gov.au/Series/F2008B00618) sets out the maximum levels of some metal and non-metal contaminants that may be present in food as a result of contact with packaging material. Standard 1.4.3 – Articles and Materials in Contact with Food (http://www.comlaw.gov.au/Details/F2008B00620) deals with food contact materials in general terms. The articles and materials in this Code refers to "*any materials in contact with food, including packaging material, which may enclose materials such as moisture absorbers, mould inhibitors, oxygen absorbers, promotional materials, writing or other graphics*". Standard 1.4.3 provides permission for these materials provided they do not cause bodily harm, distress or discomfort, but does not list specific materials that can be used in the manufacture of food packaging materials or their method of manufacture. The Australian Standard for Plastic Materials for Food Contact Use (AS 2070-1999, http://www.saiglobal.com/PDFTemp/Previews/OSH/As/as2000/2000/2070.pdf) provides a guide to industry on the production of plastic materials for food contact use. It also refers to United States and European regulations on the manufacture and use of plastics. Furthermore, Standard 3.2.2 – Food Safety Practices and General Requirements (http://www.comlaw.gov.au/Series/F2008B00576) has specific requirements for food businesses to ensure that when packaging food, only packaging material that is fit for its intended use and is not likely to cause food contamination must be used, and ensure that there is no likelihood that the food may become contaminated during the packaging process. Some specific packaging labeling requirements for meat and meat products are regulated in Standard 2.2.1 - Meat and Meat Products (http://www.comlaw.gov.au/Details/F2012C00286).

In New Zealand, hazards associated with packaging materials that come into contact with food should comply with the Animal Products Act 1999 (http://www.legislation.govt.nz/act/public/1999/0093/latest/DLM33502.html) and Food Act 2014 (http://www.foodsafety.govt.nz/policy-law/food-act-2014/). Guidance is provided for businesses such that they need to take responsibility for checking with their supplier that products meet either US requirements, Australian Standard for Plastic Materials for Food Contact Use AS2070-1999, or any other appropriate international standard recognised as acceptable by the New Zealand Ministry for Primary

Industries.

In 2010, FSANZ completed a survey of chemical migration from food contact packaging materials in Australian food (http://www.foodstandards.gov.au/science/monitoring/surveillance/pages/surveyofchemicalmigr5148. aspx) and concluded that potential harzdars chemicals such as phthalates, perfluorinated compounds, semicarbazide, acrylonitrile or vinyl chloride were not detected from packaging materials into food samples. Currently, FSANZ is undertaking work on Proposal P1034 (http://www.foodstandards.gov.au/code/proposals/Pages/P1034ChemicalMigrationfromPackagingintoF ood.aspx) to assess whether there are any unmanaged public health and safety risks relating to chemical migration from packaging into food. However, there is no specific surveys or Standard Codes in Australia and New Zealand referring specifically to active, intelligent and nanomaterials in food or meat packaging. All the materials used in food and meat packaging are therefore regulated by the current available FSANZ Standard Codes.

## 6.0  Conclusions and trends

Meat and meat products are highly nutritious foods that however also favour the growth and proliferation of spoilage and pathogen microorganisms, making them high risk in terms of quality deterioration and food safety. The oxidation of meat lipids and proteins (e.g. myoglobin) also contribute to quality deterioration of meat and meat products. Modern meat packaging should serve as an efficient tool for maintaining quality and safety, as well as increasing product value, promoting sales and imparting information (Han, 2005). Factors including price, safety, size of packaging and recyclability are most important, whereas design, convenience and utility must also be taken into account (Duizer, Robertson, & Han, 2009). Therefore, selection of appropriate packaging materials, packaging methods/conditions, and storage environments are the key to obtaining high quality packaged meat products. In addition, systems for improving the quality of raw meat before it is packaged are important to ensure the quality of the final packaged meat. For example, vitamin E supplemention to animal feed resulted high vitamin E content in the raw meat which consequently leads to an extension of retail display life by 1.6-5 days (Gray et al., 1996).

Currently, application of VP and MAP with overwrapped thermoforming films is a common practice in meat packaging to extend the shelf life and maintain good quality. Development of novel thermoforming films with improved mechanical and barrier properties and optimization of the MAP technologies are the major current research foci in this area. To achieve longer shelf-life, antimicrobial and antioxidant active packaging have been developed which positively change the conditions of the package to effectively improve the food safety and quality. According to Realini and Marcos (2014), the major technical challenge for active packaging is to develop active materials that are able to preserve their original mechanical and barrier properties after adding the active substances. The use of non-purified extracts or the use of active compounds in the form of nanoparticles can reduce the amount of active substance required and therefore help maintain the original properties of the base packaging material. The use of edible coatings, especially those which incorporate antimicrobial and antioxidant substances has great potential for meat and meat products through preventing moisture loss, delaying and controlling microbial growth and lipid oxidation, avoiding changes in texture, flavor, and color, and reducing drip loss. Selection of the appropriate coating and films for a specific meat product depends on its nature, characteristics, specific needs, costs, and benefits that this technology can offer to the manufacturers and the consumers. Some challenges remain, such as the potential negative impact on product sensory attributes, increased cost, difficulty in achieving standardized coating procedures for large scale commercial operations. Therefore, more research is needed to improve the manufacturing and application processes of edible coatings and films intended for the meat industry to ensure that their use is economically feasible and appropriate for each product.

Growing environmental awareness along with increasing oil price has led to increased demands for the development and application of alternative biobased packaging materials. Several studies have demonstrated that biobased multilayer films can guarantee the quality and shelf-life of some meat and meat products. Biobased and/or biodegradable packaging, like conventional packaging, must fulfill a number of important functions, including containment and protection of food, maintainance of sensory quality and safety, and communication of information to consumers (Peelman et al., 2014). Therefore, it is necessary to continuously investigate the combinations of different newly developed biobased materials to obtain biobased packaging solutions meeting technical and consumer requirements. Despite

the great need for and interest in utilization of biodegradable packaging, its present market is still very small compared to conventional plastics. Several barriers need to overcome, such as its high price, strong legislative mandate (still only a few materials have received EU and USA FDA approval), and poor industrial infrastructure for composting the used packaging (Maftoonazad et al., 2013).

Intelligent packaging is an emerging and exciting branch of packaging science and technology that offers great opportunities for enhancing food safety, quality, and convenience, and consequently decrease the number of retailer and consumer complaints. The introduction of quality and freshness indicators (temperature indicators, time–temperature integrators, and gas-level controls), the increased convenience of product manufacturing and distribution methods, the invention of smart permeability films, and theft and counterfeiting evidence systems will help maximize the safety and quality of food products (Han, Ho, Rodrigues, 2005). However, issues such as those relating to legislation, and economicsalso need to be addressed (Yam, Takhistov, & Miltz, 2005).

Nanotechnology products and applications can potentially revolutionise the food packaging sector, and meet many of the industry's needs in relation to innovative, strong, lightweight and active and intelligent materials (Smolander, & Chaudhry, 2010). More importantly, nanocomposites promise to expand the use of edible and biodegradable films, since the addition of nanomaterials can improve overall performance of biopolymers, enhance their mechanical, thermal and barrier properties, even at very low levels of nonomaterial addition (de Azeredo, 2009). The advancement of nanotechnology should provide new packaging solutions that can positively affect the shelf-life, quality, safety, and security of foods, which will ultimately benefit both the producers and consumers. However, more research is needed especially on the migration behaviors of nanomaterials in food and their potential impacts on consumer health and safety, and the environment (Mihindukulasuriya, & Lim, 2014).

In spite of the great possibilities existing for innovations in food packaging, it is noted that each packaging technology has peculiar drawbacks which will need to be addressed by meat and packaging scientists in the future. We can imagine that simple traditional packing will be replaced with multi-functional packaging (Sorrentino, Gorrasi, & Vittoria, 2007), such as a packaging with biodegradable, active and intelligent functions. To develop successful meat packaging systems, key product characteristics affecting stability, environmental conditions, and consumer's packaging expectations must all be taken into consideration (Youssef, (2013). A sustainable packaging solution can be achieved only if it is socially responsible, economically viable, and environmentally sound (Mihindukulasuriya, & Lim, 2014).

**Acknowledgement**

**Disclaimer**

Commercial products and manufacturers' names listed in this review are not the only ones that have been commercialized and developed in the world. The authors are not related to any of the commercial products/manufacturers that are referenced in this review.

## 7.0  References

Aberle, E. D., Forrest, J. C., Gerrard, D. E., & Mills, E. W. (2012). Principles of Meat Science (5th ed.) Dubuque, Iowa: Kendall/Hunt Publishing Co.

Ahvenainen, R. (2003). Active and intelligent packaging: an introduction. In R. Ahvenainen (Ed.), Novel food packaging techniques (pp. 5–21). Cambridge, UK: Woodhead Publishing Ltd.

Ahvenainen, R. and Hurme, E. (1997). Active and smart packaging for meeting consumer demands for quality and safety. Food Additives and Contamination, 14, 753–763.

Ahvenainen, R., Eilamo, M., & Hurme, E. (1997). Detection of improper sealing and quality deterioration of modified-atmosphere-packed pizza by a colour indicator. Food Control, 8, 177–184.

Aider, M. (2010). Chitosan application for active bio-based films production and potential in the food industry: Review. LWT - Food Science and Technology, 43(6), 837–842.

Aksu, M. İ., Kaya, M., & Ockerman, H. W. (2005). Effect of modified atmosphere packaging, storage period, and storage temperature on the residual nitrate of sliced-pastırma, dry meat product, produced from fresh meat and frozen/thawed meat. Food Chemistry, 93, 237-242.

Ali, S. W., Rajendran, S., & Joshi, M. (2011). Synthesis and characterization of chitosan and silver loaded chitosan nanoparticles for bioactive polyester. Carbohydrate Polymers, 83, 438–446.

Al-Nehlawi, A., Saldo, J., Vega, L. F., & Guri, S. (2013). Effect of high carbon dioxide atmosphere packaging and soluble gas stabilization pre-treatment on the shelf-life and quality of chicken drumsticks. Meat Science, 94, 1-8.

Althani, D., & Briggs, D. (2009). Peelable films containing nano particles. European patent EP 2097257 A1

Amna, T., Yang, J., Ryu, K-S, Hwang, I. H. (2014). Electrospun antimicrobial hybrid mats: Innovative packaging material for meat and meat-products. Journal of Food Science and Technology. DOI 10.1007/s13197-014-1508-2.

An, J., Zhang, M., Wang, S., & Tang, J. (2008). Physical, chemical and microbiological changes in stored green asparagus spears as affected by coating of silver nanoparticles-PVP. LWT – Food Science and Technology, 41(6), 1100–1107.

Anonymous (2014a). http://www.barcoding.com/faq/rfid-tag-cost.shtml, access on 16 October 2014.

Anonymous (2014b). http://www.varcode.com/, accessed on 22 October 2014

Appendinia, P., Hotchkiss, J. H. (2002). Review of antimicrobial food packaging. Innovative Food Science & Emerging Technologies, 3, 113-126.

Arvanitoyannis, I. S., & Stratakos, A. C. (2012). Application of modified atmosphere packaging and active/smart technologies to red meat and poultry: A review. Food and Bioprocess Technology, 5, 1423-1446.

Arvanitoyannis, I. S., Stratakos, A. C. (2012). Application of modified atmosphere packaging and active/smart technologies to red meat and poultry: A review. Food and Bioprocess Technology, 5(5), 1423–1446.

Arvanitoyannis, I. S., Vasiliki, K., Bouletis, A. D., & Papaloucas, C. (2011). Study of changes in physicochemical and microbiological characteristics of shrimps (*Melicertus kerathurus*) stored under modified atmosphere packaging. Anaerobe, 17, 292-294.

AUS-MEAT (2015). Handbook of Australian Meat, 7th Edition, http://www.ausmeat.com.au/custom-content/cdrom/Handbook-7th-edition/English/95F25A74-F68A-11DA-AA4B-000A95D14B6E.html

Australian Bureau of Agricultural and Resource Economics and Sciences (2013). Implementation of improvements to the National Livestock Identification System for sheep and goats: Consultation regulation impact statement, http://www.daff.gov.au/SiteCollectionDocuments/abares/nlis/nlis9oct13.pdf, accessed on 20/10/2014

Avilés, C., Juárez, M., Larsen, I. L., Rodas-González, A., & Aalhus, J. L. (2014). Effect of multiple vacuum packs on colour development and stability in beef steaks. Meat Science, 96, 124.

Azizi Samir, M. A. S., Alloin, F., & Dufresne, A. (2005). Review of recent research into cellulosic whiskers,

their properties and their application in nanocomposite field. Biomacromolecules, 6, 612–626.

Azizi Samir, M. A. S., Alloin, F., Sanchez, J. Y., & Dufresne, A. (2004). Cellulose nanocrystals reinforced poly(oxyethylene). Polymer, 45, 4149–4157.

Bagamboula, C. F., Uyttendaele, M., & Debevere, J. (2004). Inhibitory effect of thyme and basil essential oils, carvacrol, thymol, estragol, linalool and p-cymene towards *Shigella sonnei* and *S. flexneri*. Food Microbiology, 21, 33-42.

Balamurugan, S., Nattress, F. M., Baker, L. P., & Dilts, B. D. (2011). Survival of *Campylobacter jejuni* on beef and pork under vacuum packaged and retail storage conditions: Examination of the role of natural meat microflora on *C. jejuni* survival. Food Microbiology, 28, 1003-1010.

Baldwin, E.A. 2007. Surface treatments and edible coatings in food preservation. In: MS Rahman, ed. Handbook of Food Preservation, 2nd ed. New York: CRC Press, pp 477-507.

Baranenko, D.A., Kolodyaznaya, V.S., Zabelina, N.A. (2013). Effect of composition and properties of chitosan-based edible coatings on microflora of meat and meat products. ACTA Scientiarum Polonorum Technologia Alimentari, 12(2), 149-157.

Barbosa-Pereira, L., Aurrekoetxea, G. P., Angulo, I., Paseiro-Losada, P., & Cruz, J. M. (2014). Development of new active packaging films coated with natural phenolic compounds to improve the oxidative stability of beef. Meat Science, 97(2), 249–254.

Barlow, C. Y., & Morgan, D. C. (2013). Polymer film packaging for food: An environmental assessment. Resources, Conservation and Recycling, 78, 74-80.

Baublits, R. T., & Sawyer, J. T. (2010). Method of packaging fresh meat products in a low oxygen environment, meat color improvement solution and pre-packaged food product. US, US20120301577 A1.

Belcher, J. N. (2006). Industrial packaging developments for the global meat market. Meat Science, 74, 143-148.

Bell, R. G., & Bourke, B. J. (1996). Recent developments in packaging of meat and meat products. In Proceedings of the international developments in process efficiency and quality in the meat industry (pp. 99–119), Dublin Castle, Ireland.

Bharadwaj, R. K. (2001). Modeling the barrier properties of polymer-layered silicate nanocomposites. Macromolecules, 34, 9189–9192

Bingol, E. B., & Ergun, O. (2011). Effects of modified atmosphere packaging (MAP) on the microbiological quality and shelf life of ostrich meat. Meat Science, 88, 774-785.

Blacha, I., Krischek, C., & Klein, G. (2014). Influence of modified atmosphere packaging on meat quality parameters of turkey breast muscles. Journal of Food Protection, 77, 127-132.

Bodenhamer, W. T. (2000). Method and Apparatus for Selective Biological Material detection. US Patent 6,051,388. (Toxin Alert, Inc., Canada).

Bonilla, J., Vargas, M., Atarés, L., Chiralt, A. (2014). Effect of chitosan essential oil films on the storage-keeping quality of pork meat products. Food and Bioprocess Technology, 7(8), 2443-2450.

Bornez, R., Linares, M. B., & Vergara, H. (2009). Microbial quality and lipid oxidation of Manchega breed suckling lamb meat: Effect of stunning method and modified atmosphere packaging. Meat Science, 83, 383-389.

Bornez, R., Linares, M. B., & Vergara, H. (2010). Effect of different gas stunning methods on Manchega suckling lamb meat packed under different modified atmospheres. Meat Science, 84, 727-734.

Borodaev, S. V., Davidenko, O. V., Davidenko, A. V., & Ryzenko, S. P. (2003). Polymer film for food products and a packaging from a polymer film for food products. US, US20040062889 A1.

Bradley, E. L., Castle, L., & Chaudhry, Q. (2011). Applications of nanomaterials in food packaging with a consideration of opportunities for developing countries. Trends in Food Science & Technology, 22, 604–610.

Brody, A. L. (1997). Packaging of food. In A. L. Brody & K. S. Marsh (Eds.), The Wiley encyclopedia of packaging (2nd ed.). New York: Wiley (pp. 699–704) .

Brody, A. L. (2006). Nano and food packaging technologies converge. Food Technology, 60(3), 92–94.

Brody, A. L. (2007). Nanocomposite technology in food packaging. Food Technology, 61(10), 80–83.

Brody, A. L., Bugusu, B., Han, J. H., Sand, C. K., & McHugh, T. H. (2008). Innovative food packaging solutions. Journal of Food Science, 73, R107-R116.

Brody, A. L., Strupinsky, E. R., & Kline, L. R. (2001). Active packaging for food applications. Lancaster, PA, USA: Technomic PublishingCo. Inc.

Brown, M. J. (2005). Article comprising polyester multilayer film. US, US2005282025 A1.

Burnett, S.L., Heltemes, J.H., Herdt, J.G., Podtburg, T.C., Gutzmann, T.A., Brown, D.G., Christianson, R.J., Ulland, H.L.E. (2014). Antimicrobial compositions and methods for treating packaged food products. CA 2611413 C.

Buys, E. M., Nortjé, G. L., Jooste, P. J., & Von Holy, A. (2000). Combined effect of modified atmosphere bulk packaging, dietary vitamin E supplementation and microbiological contamination on colour stability of Musculus gluteus medius. Meat Science, 55, 403-411.

Cachaldora, A., Garcia, G., Lorenzo, J. M., & Garcia-Fontan, M. C. (2013). Effect of modified atmosphere and vacuum packaging on some quality characteristics and the shelf-life of "morcilla", a typical cooked blood sausage. Meat Science, 93, 220-225.

Cao, Y., Gu, W., Zhang, J., Chu, Y., Ye, X., Hu, Y., Chen, J. (2013). Effects of chitosan, aqueous extract of ginger, onion and garlic on quality and shelf life of stewed-pork during refrigerated storage. Food Chemistry, 141, 1655–1660.

Cascao-Pereira, L.G., Gebert, M.S., Mcauliffe, J.C. (2008). Oxidative protection of lipid layer biosensors. WO2007112273.

Cerisuelo, J. P., Bermúdez, J. M., Aucejo, S., Catalá, R., Gavara, R., & Hernández-Muñoz, P. (2013). Describing and modeling the release of an antimicrobial agent from an active PP/EVOH/PP package for salmon. Journal of Food Engineering, 116, 352-361.

Chao, Z.H. (2013). Nano preservation method for chilled fresh meat. CN103385282 A.

Chawengkijwanich, C., & Hayata, Y. (2008). Development of TiO2 powder-coated food packaging film and its ability to inactivate Escherichia coli in vitro and in actual tests. International Journal of Food Microbiology, 123, 288–292.

Chen, E. C., & Wu, T. M. (2007). Isothermal crystallization kinetics and thermal behavior of poly(3-caprolactone)/multi-walled carbon nanotube composites. Polymer Degradation and Stability, 92, 1009–1015

Chen, J. C. (2007). Vacuum skin packaging structure with high oxygen permeability. US, US2010055275 A1.

Chen, J.H., Ren, Y., Seow, J., Liu, T., Bang, W.S., Yuk, H.G. (2012). Intervention Technologies for Ensuring Microbiological Safety of Meat: Current and Future Trends. Comprehensive Reviews in Food Science and Food Safety, 11(2), 119–132.

Chen, Q., Li, H., Zhao, J. & O, Q. (2014). Nanofiber material for pork preservation. China patent CN 103757727 A.

Cheng, Q., Li, C., Pavlinek, V., Saha, P., & Wang, H. (2006). Surfacemodified antibacterial $TiO_2/Ag^+$ nanoparticles: preparation and properties. Applied Surface Science, 252, 4154–4160.

Cherevko, O. I., Kovalenko, V. O., Horban, V. H., Yevlash, V. V., & Rozanova, K. D. (2005). Method of making half-finished products of beef, poultry meat and other raw meat material. UA, UA72125 A.

Chouliara, E., Badeka, A., Savvaidis, I., & Kontominas, M. G. (2007). Combined effect of irradiation and modified atmosphere packaging on shelf-life extension of chicken breast meat: microbiological, chemical and sensory changes. European Food Research and Technology, 226, 877-888.

Clark, M.N., Baughan, J.S. (2012). Nanotechnology regulation of food packaging. Packaginglaw.com. http://www.packaginglaw.com/3378_.shtml.

Claudia, R.-C., & Francisco, J.-C. (2010). Effect of an argon-containing packaging atmosphere on the quality of fresh pork sausages during refrigerated storage. Food Control, 21, 1331-1337.

Claus, J. R., & Du, C. (2013). Nitrite-embedded packaging film effects on fresh and frozen beef color development and stability as influenced by meat age and muscle type. Meat Science, 95, 526-535.

Claus, J., & Du, C. (2014). Nitrite-embedded packaging film effects on beef color as influenced by meat age and muscle type. Meat Science, 96, 457-458.

Coles, R., McDowell, D., & Kirwan, M. J. (2003). Food packaging technology. Oxford: Blackwell.

Coma, V. (2008). Bioactive packaging technologies for extended shelf life of meat-based products. Meat Science, 78, 90–103.

Commission Regulation (EU) No 10/2011.  Plastic materials and articles intended to come into contact with food. http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CONSLEG:2011R0010:20111230:EN:PDF, accessed on 12/01/2015

Cook, A.J., & Fairweather , J. R. (2007). Intentions of New Zealanders to purchase lamb or beef made using nanotechnology. British Food Journal, 109, 675– 688

Cook, A.J., Kerr, G.N. and Moore, K. (2002). Attitudes and intentions towards purchasing GM food, Journal of Economic Psychology, 23, 557–572.

Cooksey, K. (2001). Antimicrobial food packaging materials. Additives for Polymers, 8, 6–10.

Cornforth, D., & Hunt, M. (2008). Low-oxygen packaging of fresh meat with carbon monoxide. AMSA white paper series, 2.

Coton, M., Joffraud, J. J., Mekhtiche, L., Leroi, F., & Coton, E. (2013). Biodiversity and dynamics of the bacterial community of packaged king scallop (*Pecten maximus*) meat during cold storage. Food Microbiology, 35, 99-107.

Crippa, A., Sydenstricker, T. H. D., & Amico, S. C. (2007). Performance of multilayer films of thermoformed packages. Polímeros, 17, 188-193.

DAFF (2013). Department of Agriculture, Fisheries and Forestry, Australia food statistics 2011-2012.http://www.agriculture.gov.au/SiteCollectionDocuments/ag-food/publications/food-stats/daff-foodstats-2011-12.pdf (accessed on 8/10/2014)

Dainelli, D., Gontard, N., Spyropoulos, D., Zondervan-van den Beukend, E., Tobback, P. (2008). Active and intelligent food packaging: legal aspects and safety concerns. Trends in Food Science & Technology, 19, S103-S112.

Damm, C., Munstedt, H., & Rosch, A. (2008). The antimicrobial efficacy of polyamide 6/silver-nano- and microcomposites. Materials Chemistry and Physics, 108, 61–66.

Daponte, T., Janssens, M. (2005). Masterbatch composition containing nano scalar zinc oxide for the production of transparent polyolefin films with UV-barrier properties. European paten EP 1609816 A1

Dawson, P., Cooksey, K., Mangalassary, S. (2012). Environmentally compatible packaging of muscle foods. Cp. 17. In Advances in Meat, Poultry and Seafood Packaging edited by Joseph P. Kerry. Woodhead Publishing.

de Azeredo, H. M. C. (2009). Nanocomposites for food packaging applications. Food Research International, 42, 1240–1253

de Azeredo, H. M. C. (2013). Antimicrobial nanostructures in food packaging. Trends in Food Science & Technology 30, 56–69.

De La Puerta M. C. C. N., Gutierrez, B.C., & Sanchez, J. C. (2010). Smart packaging for detecting microorganisms. Patent WO 2010128178 A1.

Dehnad, D., Mirzaei, H., Emam-Djomeh, Z., Jafaria, S.-M., Dadashi, S. 2014. Thermal and antimicrobial properties of chitosan–nanocellulose films for extending shelf life of ground meat. Carbohydrate Polymers, 109,148–154.

Delles, R. M., & Xiong, Y. L. (2014). The effect of protein oxidation on hydration and water-binding in pork packaged in an oxygen-enriched atmosphere. Meat Science, 97, 181-188.

Deng, Q. and Zhao, Y. (2011). Physicochemical, nutritional and antimicrobial properties of wine grape pomace extracts based films. Journal of Food Science, 76(3), E309-317.

Devatkal, S. K., Thorat, P., & Manjunatha, M. (2014). Effect of vacuum packaging and pomegranate peel extract on quality aspects of ground goat meat and nuggets.. Journal of Food Science and Technology, 51, 2685-2691.

Devlieghere, F., Vermeulen, A., Debevere, J. (2004). Chitosan: Antimicrobial activity, interactions with food components and applicability as a coating on fruit and vegetables. Food Microbiology, 21, 703-714.

Djenane, D., Martínez, L., Sánchez-Escalante, A., Beltrán, J. A., & Roncalés, P. (2004). Antioxidant effect of carnosine and carnitine in fresh beef steaks stored under modified atmosphere. Food Chemistry, 85, 453-459.

Djenane, D., Sánchez-Escalante, A., Beltrán, J. A., & Roncalés, P. (2002). Ability of α-tocopherol, taurine and rosemary, in combination with vitamin C, to increase the oxidative stability of beef steaks packaged in modified atmosphere. Food Chemistry, 76, 407-415.

Djenane, D., Sánchez-Escalante, A., Beltrán, J. A., & Roncalés, P. (2003a). Extension of the shelf life of beef steaks packaged in a modified atmosphere by treatment with rosemary and displayed under UV-free lighting. Meat Science, 64, 417-426.

Djenane, D., Sánchez-Escalante, A., Beltrán, J. A., & Roncalés, P. (2003b). The shelf-life of beef steaks treated with dl-lactic acid and antioxidants and stored under modified atmospheres. Food Microbiology, 20, 1-7.

Dogu-Baykut, E., & Gunes, G. (2014). Quality of ready-to-cook marinated chicken drumsticks as affected by modified atmosphere packaging during refrigerated storage. Journal of Food Processing and Preservation, 38, 615-621.

Dorman, H. J. D., & Deans, S. G. (2000). Antimicrobial agents from plants: antibacterial activity of plant volatile oils. Journal of Applied Microbiology, 88, 308-316.

Duan, J., Zhao, Y. (2010). Edible Coatings and Films and Their Applications on Frozen Foods. In "Handbook of Frozen Food Processing and Packaging". Ed. Sun, D. CRC Press/Taylor & Francis.

Duizer, L.M., Robertson, T., Han, J. (2009). Requirements for packaging from an ageing consumer's perspective. Packaging Technology and Science, 22, 187–197.

Duncan, P.W., Robert, T.I. (2001). Meat product packaging. WO 2001049121 A1.

Duncan, T. V. (2011). Applications of nanotechnology in food packaging and food safety: barrier materials, antimicrobials and sensors. Journal of Colloid and Interface Science, 363, 1-24.

Durdag, K., Pendleton, B., Hamlyn, R., Gunn, V., Etchells, M. (2013). Biodegradable polymer non-woven absorbent pad with absorbency and antimicrobial chemistry. US patent US 20130295315 A1.

Ebner, C. L., & Stockley, W. (2006) Vacuum packaging of a meat product using a film having a carbon dioxide scavenger. US, US20080138478 A1.

Ebner, C.L., Matthews, A.E., Millwood, T.O. (2006). Oxygen scavenger compositions derived from isophthalic acid and/or terephthalic acid monomers or derivatives thereof. US 20067452601.

EFSA (2009). The potential risks arising from nanoscience and nanotechnologies on food and feed safety. The EFSA Journal, 958, 1-39. http://www.efsa.europa.eu/en/scdocs/doc/958.pdf

Egan, A. F., Eustace, I. J., & Shay, B. J. Meat packaging–maintaining the quality and prolonging the storage life of chilled beef, pork and lamb. In: Meat 88: Proceedings of Industry Day, Brisbane, 1988. pp 68-75.

Egan, A. F., Eustace, I. J., Shay, B. J. (1988). Meat packaging - maintaining the quality and prolonging the storage life of chilled beef, pork and lamb. Proceedings of Industry Day: Part of the 34th International Congress of Meat Science and Technology, Brisbane, pp. 68-75.

Eilert, S. J. (2005). New packaging technologies for the 21st century. Meat Science, 71, 122-127.

Elsabee, M.Z., Abdou, E.S. (2013). Chitosan based edible films and coatings: A review. Materials Science and Engineering C, 33, 1819–1841.

Emamifar, A., Kadivar, M., Shahedi, M., & Soleimanian-Zad, S. (2010). Evaluation of nanocomposite packaging containing Ag and ZnO on shelf life of fresh orange juice. Innovative Food Science and Emerging Technologies, 11, 742–748.

Enser, M. (1987). What is lipid oxidation. Food Science Technology Today, 1, 151–153.

Esmer, O. K., Irkin, R., Degirmencioglu, N., & Degirmencioglu, A. (2011). The effects of modified atmosphere gas composition on microbiological criteria, color and oxidation values of minced beef meat. Meat Science, 88, 221-226.

Ettinger, D. J. (2002). Active and Intelligent Packaging: A U.S. and EU Perspective. From Packaginglaw.com, http://www.packaginglaw.com/2558_.shtml.

Ettinger, D.J. and Clark, M. N. (2015) The regulation of food packaging materials in Japan. http://www.packaginglaw.com/3383_.shtml (access on 23/01/2015)

EU Guidance to the Commission Regulation (EC) No 450/2009. Active and intelligent materials and articles intended to come into contact with food. http://ec.europa.eu/food/food/chemicalsafety/foodcontact/docs/guidance_active_and_intelligent _scofcah_231111_en.pdf, accessed on 12/01/2015

EU. 1995. Directive No. 95/2/CE. Commission Decision 20/02/1995, on food additives other than colours and sweeteners. Off. J. L61:0001–0040.

EU. 2009. Guidance to the commission regulation (EC) No 450/2009 of 29 May 2009 on active and intelligent materials and articles intended to come into contact with food. Version 10. European Commission Health and Consumers Directorate-General Directorate E-Safety of the Food chain. E6-Innovation and sustainability.

Evans, S.P., Luthra, V.K., Santhanam, V., Kalathur, S., Sloan, A.R. (2003). Rapid oxygen absorption by using activators. US20036616861.

Farber, J. M. (1991). Microbiological aspects of modified-atmosphere packaging technology - a review Journal of Food Protection, 54, 58-70.

Faustman, C., Cassens, R. G. (1990): The biochemical basis for discoloration in freshmeat: a review, Journal of Muscle Foods, 1, 217–243.

FDA. (2004). Agency response letter. GRAS Notice No. GRN 000143. http://www.fda.gov/Food/IngredientsPackagingLabeling/GRAS/NoticeInventory/ucm153974.htm, accessed on 09/02/2015.

FDA. (2006). Food additives permitted for direct addition to food for human consumption 21 CFR172, subpart C. Coatings, films and related substances.

FDA. (2014a). Considering whether an FDA-regulated product involves the application of nanotechnology. Guidance for industry (http://www.fda.gov/RegulatoryInformation/Guidances/ucm257698.htm). Page Last Updated: 06/27/2014.

FDA. (2014b). FDA's approach to regulation of nanotechnology products. (http://www.fda.gov/ScienceResearch/SpecialTopics/Nanotechnology/ucm301114.htm). Page Last Updated: 06/24/2014.

Félix, J. S., Manzoli, J. E., Padula, M., & Monteiro, M. (2014). Evaluation of different conditions of contact for caprolactam migration from multilayer polyamide films into food simulants. Packaging Technology and Science, 27, 457-466.

Ferioli, F., Caboni, M. F., & Dutta, P. C. (2008). Evaluation of cholesterol and lipid oxidation in raw and cooked minced beef stored under oxygen-enriched atmosphere. Meat Science, 80, 681-685.

Fernandes, R. d., P., Freire, M. T., Paula, E. S., Kanashiro, A. L., Catunda, F. A., Rosa, A. F., Balieiro, J. C., & Trindade, M. A. (2014). Stability of lamb loin stored under refrigeration and packed in different modified atmosphere packaging systems. Meat Science, 96, 554-561.

Fernández, A., Picouet, P., & Lloret, E. (2010). Reduction of the spoilage-related microflora in absorbent pads by silver nanotechnology during modified atmosphere packaging of beef meat. Journal of Food Protection, 12, 2148-2349

Fernández, K., Aspe, E., & Roeckel, M. (2009). Shelf-life extension on fillets of Atlantic Salmon (*Salmo salar*) using natural additives, superchilling and modified atmosphere packaging. Food Control, 20, 1036-1042.

Framework Regulation (EC) No 1935/2004, Materials and articles which come into contact with food,

http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CONSLEG:2004R1935:20090807:EN:PDF, accessed on 23/01/2015.

Franssen, L.R., Krochta, J. M. (2003). Edible coatings containing natural antimicrobials for processed foods. In S. Roller (Ed.), Natural antimicrobials for minimal processing of foods (pp. 250-262). Boca Raton: CRC Press.

Fraqueza, M. J., & Barreto, A. S. (2009). The effect on turkey meat shelf life of modified-atmosphere packaging with an argon mixture. Poultry Science, 88, 1991-1998.

Fraqueza, M. J., Alfaia, C. M., & Barreto, A. S. (2012). Biogenic amine formation in turkey meat under modified atmosphere packaging with extended shelf life: Index of freshness. Poultry Science, 91, 1465-1472.

FSANZ (2014). International regulations for food contact materials – P1034, http://www.foodstandards.gov.au/code/proposals/Documents/P1034-Packaging-CFS-SD2.pdf, accessed on 23/01/2015.

FSANZ. (2009). Assessment of microbiological hazards associated with the four main meat species, http://www.foodstandards.gov.au/code/proposals/documents/P1005%20PPPS%20for%20Meat%20_%20Meat%20Products%201AR%20SD1.pdf (accessed on 8/10/2014).

Galić, K., Ščetar, M., & Kurek, M. (2011). The benefits of processing and packaging. Trends in Food Science & Technology, 22, 127-137.

Gamble, J., Muggleston, S., Hedderly, D., Parminter, T. and Richardson-Harman, N. (2000). Genetic engineering – the publics' point-of-view. Mount Albert Research Centre. Horticulture and Food Research Institute of New Zealand Limited, Auckland

Garcia-Esteban, M., Ansorena, D., & Astiasaran, I. (2004). Comparison of modified atmosphere packaging and vacuum packaging for long period storage of dry-cured ham: effects on colour, texture and microbiological quality. Meat Science, 67, 57-63.

Gennadios, A., Hanna, M.A., Kurth, L.B. (1997). Application of edible coatings on meats, poultry and seafoods: a review. LWT- Food Science and Technology, 30, 337–350.

Georgala, D. L., & Davidson, C. L. (1970). Food package. British Patent 1199998.

Georgescu, I., Cobianu, C., Dumitru, V-G. (2008). Intelligent packaging method and system based on acoustic wave devices. US patent US 7755489 B2.

Gill, C. (1996). Extending the storage life of raw chilled meats. Meat Science, 43, 99-109.

Glitsch, K. (2000). Consumer perceptions of fresh meat quality: cross-national comparison. British Food Journal, 102, 177–194.

Goldsmith, R.M., Goldsmith, C., Woodaman, J.G., Park, D.L., & Ayala, C.E. (1999). Food Sentinel System TM. World Intellectual Property Organization. WO/1999/014598 Patent.

Gomez, M., & Lorenzo, J. M. (2012). Effect of packaging conditions on shelf-life of fresh foal meat. Meat Science, 91, 513-520.

Gomez-Estaca, J., Lopez-de-Dicastillo, C., Hernandez-Mu~noz, P., Catala, R., Gavara, R. (2014). Advances in antioxidant active food packaging. Trends in Food Science & Technology, 35, 42-51.

Gould, G. W., Measures, J. C., Wilkie, D. R., Meares P. (1977).Water relations in single cells. Philosophical Transactions of the Royal Society B, 278, 151–166.

Grah, M. D. (2011). Increasing the gas transmission rate of a film comprising fullerenes. Canada patent CA 2618887 C.

Gray, J. I., Gomaa, E. A., & Buckley, D. J. (1996). Oxidative quality and shelf life of meats. Meat Science, 43, 111-123.

Greengrass, J. (1999) Packaging materials for MAP of foods. Principles and applications of modified atmosphere packaging of food. Aspen, Gaithersburg.

Grobbel, J., Dikeman, M., Hunt, M., & Milliken, G. Different packaging environments alter tenderness and sensory traits from non-enhanced and injection-enhanced beef. In: Proceedings 53rd international congress of meat science and technology, 2007. pp 527-528

Grund, H., Lang, H., & Schauer, H. (2001). Five-layered, biaxially-oriented, sealable tubular film for the packaging and wrapping of paste-like foodstuffs meat and meat with bones and use thereof. US, US6998160 B2.

Grunert, K. G., & Valli, C. (2001). Designer-made meat and dairy products: consumer-led product development. Livestock Production Science, 72, 83–98.

Guarda, A., Valenzuela, X., Ramirez, A., Galotto, M.J. (2014). Process for obtaining a film that comprises the incorporation of natural antimicrobial agents in a polymeric structure. US 20140008836 A1.

Gunes, G., Ozturk, A., Yilmaz, N., & Ozcelik, B. (2011). Maintenance of safety and quality of refrigerated ready-to-cook seasoned ground beef product (meatball) by combining gamma irradiation with modified atmosphere packaging. Journal of Food Science, 76, M413-420.

Guo, M., Jin, T.Z., Wang, L., Joseph Scullen, O., Sommers, C.H. (2014). Antimicrobial films and coatings for inactivation of Listeria innocua on ready-to-eat deli turkey meat. Food Control, 40, 64–70.

Guo, M., Jin, T.Z., Yang, Y. (2014). Antimicrobial polylactic acid packaging films against listeria and salmonella in culture medium and on ready-to-eat meat. Food and Bioprocess Technology, 7(11), 3293-3307.

Gutiérrez, J. I., Tejeda, J. F., Carrapiso, A. I., Petrón, M. J., Lara, M. S., & Andrés, A. I. (2011). Shelf life of Merino lamb meat retail packaged under atmospheres of various compositions. International Journal of Food Science & Technology, 46, 492-499.

Hagenmaier, R.E., Shaw, P.E. (1991). Permeability of shellac coatings to gases and water vapor. Journal of Agricultural and Food Chemistry 39 (5), 825-829.

Han, J. H. (2005). Antimicrobial packaging systems. In: Han, J.H., ed. Innovations in Food Packaging, Elsevier Academic Press: Amsterdam, The Netherlands, pp. 80–107.

Han, J. H., Ho, C. H. L. & Rodrigues, E. t. (2005). Intelligent packaging. In: Han, J. H. (eds). Innovative in food packaging. Elsevier Academic Press: Amsterdam, The Netherlands, pp. 138–155.

Haruo, O., & Toshio, H. (2006) High-speed vacuum individual packaging method for portion of meat. US, US2006045941 A1.

He, J., Kunitake, T., & Nakao, A. (2003). Facile in situ synthesis of noble metal nanoparticles in porous cellulose fibers. Chemistry of Materials, 15, 4401e4406

He, S., Yang, Q., Ren, X., Zi1, J., Lu, S., Wang, S., Zhang, Y., Wan, Y. (2014). antimicrobial efficiency of chitosan solutions and coatings incorporated with clove oil and/or ethylenediaminetetraacetate. Journal of Food Safety, 34(4), 345–352.

Helbert, W., Cavaille, C. Y., & Dufresne, A. (1996). Thermoplastic nanocomposites filled with wheat straw cellulose whiskers. Part I: processing and mechanical behaviour. Polymer Composites, 17(4), 604–611

Hempel, A., Papkovsky, D., & Kerry, J. (2013). Use of optical oxygen sensors in non-destructively determining the levels of oxygen present in combined vacuum and modified atmosphere packaged pre-cooked convenience-style foods and the use of ethanol emitters to extend product shelf-life. Foods, 2, 507-520.

Herbert, U., Rossaint, S., Khanna, M. A., & Kreyenschmidt, J. (2013). Comparison of argon-based and nitrogen-based modified atmosphere packaging on bacterial growth and product quality of chicken breast fillets. Poultry Science, 92, 1348-1356.

Hertog, M. L. A. T. M., Belgium, K. U. L., & Banks, N. H. (2003) Improving MAP through conceptual models. In: Ahvenainen R (ed) Novel food packaging techniques. CRC, Boca Raton, Boston, New York, Washington, DC pp 338-346.

Hettiarachchy, N.S., Stachithanadam, E. (2005). Organic acids incorporated edible antimicrobial films. EP 1545225 A1.

Hintlian, C. B., & Hotchkiss, J. H. (1986). The safety of modified atmosphere packaging - a review. Food Technology, 40, 70-76.

Holst, E.J., Smit, N.R., Summerfield, J.W. (2012). Fresh meat color in vacuum packaged or modified atmosphere packaged fresh meat products. US20120027896 A1.

Holte, B. (1993). An Apparatus for Indicating the Presence of CO2 and a Method of Measuring and Indicating Bacterial Activity within a Container or Bag. PCT International Patent Application WO 93/15402.

Honeybourne, C. L. (1993). Food Spoilage Detection Method. PCT International Patent Application WO 93/15403

Hong, S. I., & Park, W. S. (2000). Use of color indicators as an active packaging system for evaluating kimchi fermentation. Journal of Food Engineering, 46, 67–72.

Horan, T. J. (2000). Method for determining deleterious bacterial growth in packaged food utilizing hydrophilic polymers, US Patent 6149952.

Hornsby, W., & Trost, J. (2003) System and method for packaging meat products in low oxygen environment. US, US20030108643 A1.

Huang, B.Y., Zhou, Q. (2013). Potato modified starch and preparation method and application thereof. CN101864094 B.

Huang, H.B., Huang, G.Z., Huang, H.T., Zhou, X.J. (2013). Antibacterial preservation technology for conventional pickled bacon products. CN103238655 A.

Hurme, E., Sipiläinen-Malm,. T., Ahvenainen, R., and Nielsen, T. (2002). 'Active and intelligent packaging'. In: *Minimal Processing Technologies in the Food Industry*. T. Ohlsson and N. Bengtsson (eds), Woodhead Publishing Limited, Cambridge, England, pp. 87–123.

Ikemoto, Y., & Tsubouchi, K. (2005). Gas barrier shrink film and its manufacturing method. JP, JP2005111791 A.

Jakobsen, M., & Bertelsen, G. (2000). Colour stability and lipid oxidation of fresh beef. Development of a response surface model for predicting the effects of temperature, storage time, and modified atmosphere composition. Meat Science, 54, 49-57.

Jayas, D., & Jeyamkondan, S. (2002). PH—postharvest technology: modified atmosphere storage of grains meats fruits and vegetables. Biosystems Engineering, 82, 235-251.

Jayasena, D.D., Jo, C. (2013). Essential oils as potential antimicrobial agents in meat and meat products: A review. Trends in Food Science & Technology, 34, 96-108.

Jayasingh, P., Cornforth, D. P., Carpenter, C. E., & Whittier, D. (2001). Evaluation of carbon monoxide treatment in modified atmosphere packaging or vacuum packaging to increase color stability of fresh beef. Meat Science, 59, 317-324.

Jenkins, W. A., & Harrington, J. P. (1991). Packaging foods with plastics. Technomic Pub. Co.

Jensen, J. S. (2005). Protecting quality of sliced meats. New Food, 8, 70,72-73.

Jeremiah, L. (2001). Packaging alternatives to deliver fresh meats using short-or long-term distribution. Food Research International, 34, 749-772.

John, L., Cornforth, D., Carpenter, C. E., Sorheim, O., Pettee, B. C., & Whittier, D. R. (2005). Color and thiobarbituric acid values of cooked top sirloin steaks packaged in modified atmospheres of 80% oxygen, or 0.4% carbon monoxide, or vacuum. Meat Science, 69, 441-449.

John, L., Cornforth, D., Carpenter, C., Sorheim, O., Pettee, B., & Whittier, D. (2004). Comparison of color and thiobarbituric acid values of cooked hamburger patties after storage of fresh beef chubs in modified atmospheres. Journal of Food Science, 69, C608-C614.

Jongberg, S., Skov, S. H., Tørngren, M. A., Skibsted, L. H., & Lund, M. N. (2011). Effect of white grape extract and modified atmosphere packaging on lipid and protein oxidation in chill stored beef patties. Food Chemistry, 128, 276-283.

Jongberg, S., Wen, J., Tørngren, M. A., & Lund, M. N. (2014). Effect of high-oxygen atmosphere packaging on oxidative stability and sensory quality of two chicken muscles during chill storage. Food Packaging and Shelf Life, 1, 38-48.

Jung, J., Zhao Y. (2012). Comparison in antioxidant action between α-chitosan and β-chitosan at a wide range of molecular weight and chitosan concentration. Bioorganic and Medicinal Chemistry, 20(9), 2905-2911.

Jung, J., Zhao Y. (2013). Impact of the structural differences between α- and β-chitosan on their depolymerizing reaction and antibacterial activity. Journal of Agricultural and Food Chemistry, 61(37), 8783-8789.

Júnior, A.V., Fronza, N., Foralosso, F.B., Dezen, D., Huber, E., Zimnoch dos Santos, J.H., Machado, R.A., Quadri, M.G.N. (2014). Biodegradable duo-functional active film: antioxidant and antimicrobial actions for the conservation of beef. Food and Bioprocess Technology, 8(1), 75-87.

Kanatt, S.R., Rao, M.R., Chawl, S.P., Sharm, A. (2014). Effects of chitosan coating on shelf-life of ready-to-cook meat products during chilled storage. LWT - Food Science and Technology, 53(1), 321–326.

Kanatt, S.R., Rao, M.S., Chawl, S.P., Sharma, A. (2012). Active chitosan–polyvinyl alcohol films with natural extracts. Food Hydrocolloids, 29(2), 290–297.

Kannan, G., Chawan, C.B., Kouakou, B., Gelaye, B. (2002). Influence of packaging method and storage time on shear value and mechanical strength of intramuscular connective tissue of chevon. Journal of Animal Science, 80, 2383–2389

Kaplan, D.L., Singh, A. (2007). Antioxidant-functionalized polymers. US20070010632 A1.

Karabagias, I., Badeka, A., & Kontominas, M. G. (2011). Shelf life extension of lamb meat using thyme or oregano essential oils and modified atmosphere packaging. Meat Science, 88, 109-116.

Keller and Heckman LLP's Packaging Practice Group. (2002). Special focus technical considerations in the regulation of active packaging in the U.S. Jun 2002. http://www.packaginglaw.com/2559_.shtml.

Kerry, J. P., O'Grady, M. N., & Hogan, S. A. (2006). Past, current and potential utilisation of active and intelligent packaging systems for meat and muscle-based products: A review. Meat Science, 74, 113-130.

Kester, J.J., Fennema, O.R. (1986). Edible films and coatings: a review. Food Technology, 40, 47-59.

Khan, A., Huq, T., Khan, R.A., Riedl, B., Lacroix, M. (2014). Nanocellulose-based composites and bioactive agents for food packaging. Critical Reviews in Food Science and Nutrition, 54(2), 163-174.

Khan, M.I., Adres, M.N., Tariq, M.R., Sohaib, M. (2013). Application of edible coating for improving meat quality: A review. Pakistani Journal of Food Science, 23(2), 2013, 71-79.

Khwaldia, K., Perez, C., Banon, S., Desobry, S., Hardy, J. (2004). Milk proteins for edible films and coatings. Critical Reviews in Food Science and Nutrition, 44, 239-251.

Kim, Y. H. B., Stuart, A., Rosenvold, K., & Maclennan, G. (2013). Effect of forage and retail packaging types on meat quality of long-term chilled lamb loins. Journal of Animal Science, 91, 5998-6007.

Kim, Y. H., Huff-Lonergan, E., Sebranek, J. G., & Lonergan, S. M. (2010). High-oxygen modified atmosphere packaging system induces lipid and myoglobin oxidation and protein polymerization. Meat Science, 85, 759-767.

Koenig, M. Effern, V. Redmann-Schmid, S. & Lutz, W. (2008). Food casing based on cellulose hydrate with nanoparticles. US patent US 20080145576 A1.

Koh, H.C., Park, J.S., Jeong, M.A., Hwang, H.Y., Hong, Y.T., Ha, S.Y. (2008). Preparation and gas permeation properties of biodegradable polymer/layered silicate nanocomposite membranes. Desalination, 233, 201–209.

Koutsoumanis, K., Stamatiou, A., Skandamis, P., & Nychas, G.-J.E. (2006). Development of a microbial model for the combined effect of temperature and pH on spoilage of ground meat and validation of the model under dynamic temperature conditions. Applied Environmental Microbiology, 72, 124–134.

Krause, T. R., Sebranek, J., Rust, R., & Honeyman, M. (2003). Use of carbon monoxide packaging for improving the shelf life of pork. Journal of Food Science, 68, 2596-2603.

Kress-Rogers, E. (1993). The maker concept: frying oil monitor and meat freshness indicator. In: E. Kress-Rogers (ed.), Instrumentation and Sensors for the Food Industry. Boston, MA, USA: Butterworth Heinemann.

Kumanayaka, T. O., Parthasarathy, R., & Jollands, M. (2010). Accelerating effect of montmorillonite on oxidative degradation of polyethylene nanocomposites. Polymer Degradation and Stability, 95, 672–676.

Kumar, R. & Munstedt, H. (2005). Silver ion release from antimicrobial polyamide/silver composites. Biomaterials, 26, 2081–2088.

Kuorwel, K.K., Cran, M.J., Sonneveld, K., Miltz, J., Bigger, S.W. (2011). Antimicrobial activity of biodegradable polysaccharide and protein-based films containing active agents. Journal of Food Science, 76(3), R90-R102.

Labuza, T. Tp. (1968). Sorption phenomena in foods. Food Technology, 22, 263–265, 268, 270, 272.

Ladikos, D. & Lougovois V. (1990). Lipid oxidation in muscle foods: a review. Food Chemistry, 35, 295–314.

Lagaron, J. M. and Lopez-Rubio, A. (2011). Nanotechnology for bioplastics: opportunities, challenges and strategies. Trends in Food Science & Technology 22, 611–617.

Lagaron, J. M., & Fendler, A. (2009). High water barrier nanobiocomposites of metil cellulose and chitosan for film and coating applications. Journal of Plastic Film and Sheeting, 25, 47–59

Lagaron, J. M., Cabedo, L., Cava, D., Feijoo, J. L., Gavara, R., & Gimenez, E. (2005). Improving packaged food quality and safety. Part 2: nanocomposites. Food Additives and Contaminants, 22, 994–998.

Lagaron, J. M., Catala, R., & Gavara, R. (2004). Structural characteristics defining high barrier polymeric materials. Materials Science and Technology, 20, 1–7.

Lagerstedt, A., Lundstrom, K., & Lindahl, G. (2011). Influence of vacuum or high-oxygen modified atmosphere packaging on quality of beef *M. longissimus dorsi* steaks after different ageing times. Meat Science, 87, 101-106.

Laimer, W. (2011) Protective gas for packaging meat or sausages. DE, DE102011122769 A1.

Landrock, A., & Wallace, G. (1955). Discoloration of fresh red meat and its relationship to film oxygen permeability. Food Technology, 9, 194-196.

Lauzurica, S., de la Fuente, J., Diaz, M. T., Alvarez, I., Perez, C., & Caneque, V. (2005). Effect of dietary supplementation of vitamin E on characteristics of lamb meat packed under modified atmosphere. Meat Science, 70, 639-646.

Ledward, D. A. (1970). Metmyoglobin formation in beef stored in carbon dioxide enriched and oxygen depleted atmospheres. Journal of Food Science, 35, 33-37.

Lee, D.S. 2014. Antioxidant packaging system. In J. H. Han (Ed.), Innovations in food packaging (pp. 111–131). San Diego, USA: Academic Press.

Lee, J. Y. (2005). Packaging meat in vacuum by packaging meat with bamboo leaf slices or bamboo leaf powder prior to vacuum packaging of meat, capable of reducing product spoilage. KR20050019586 A.

Leygonie, C., Britz, T. J., & Hoffman, L. C. (2011). Protein and lipid oxidative stability of fresh ostrich M. Iliofibularis packaged under different modified atmospheric packaging conditions. Food Chemistry, 127, 1659-1667.

Li, X., Liu, A., Ye, R., Wang, Y., Wang, W. (2015). Fabrication of gelatin–laponite composite films: Effect of the concentration of laponite on physical properties and the freshness of meat during storage. Food Hydrocolloids, 44, 390–398.

Lim, S.L., Wan Rosli, W.I. (2014). Nutritional composition and lipid oxidation stability of beef patties packed with biodegradable and non-biodegradable materials. Sains Malaysiana, 43(8), 1197–1203.

Lima, M. M. D., & Borsali, R. (2004). Rodlike cellulose microcrystals: structure, properties, and applications. Macromolecular Rapid Communications, 25, 771–787.

Limbo, S., Torri, L., Sinelli, N., Franzetti, L., & Casiraghi, E. (2010). Evaluation and predictive modeling of shelf life of minced beef stored in high-oxygen modified atmosphere packaging at different temperatures. Meat Science, 84, 129-136.

Lin, D., Zhao, Y. (2007). Innovations in the development and application of edible coatings for fresh and minimally processed fruits and vegetables. Comprehensive Food Science and Food Safety, 6, 60-75.

Lin, J., Su, B.H., Chen, J.B., Ye, X.Y. (2013). Edible composite preservative film applied to preservation of fresh pork in supermarket. CN102977414 A.

Linares, M. B., & Vergara, H. (2012). Effect of gas stunning and modified-atmosphere packaging on the quality of meat from Spanish Manchego light lamb. Small Ruminant Research, 108, 87-94.

Linares, M. B., Berruga, M. I., Bornez, R., & Vergara, H. (2007). Lipid oxidation in lamb meat: Effect of the weight, handling previous slaughter and modified atmospheres. Meat Science, 76, 715-720.

Linares, M. B., Bórnez, R., & Vergara, H. (2008). Effect of stunning systems on meat quality of Manchego suckling lamb packed under modified atmospheres. Meat Science, 78, 279-287.

Lischefski, A. J., & Nelson, K. P. (2008). Breathable packaging film having enhanced thermoformability. US, US8449984 B2.

Liu, C., Zhang, Y., Yang, X., Liang, R., Mao, Y., Hou, X., Lu, X., & Luo, X. (2014). Potential mechanisms of carbon monoxide and high oxygen packaging in maintaining color stability of different bovine muscles. Meat Science, 97, 189-196.

Liu, W., Zang, Z.Y. (2012). Edible soy protein casing film and preparation method thereof. CN101715870 B.

Liu, X.H., Xie, S. Y., Zhou, L. B., Yang, Y., Li, H. B. (2013). Preparation method of nano $TiO_2$ powder and method for preparing oxygen gas indicator from nano $TiO_2$ powder. China patent CN103641163A

Llorens, A., Lloret, E., Picouet, P.A., Trbojevich, R., and Fernandez, A. (2012). Metallic-based micro and nanocomposites in food contact materials and active food packaging. Trends in Food Science & Technology, 24, 19–29.

Lloret, E., Picouet, P., & Fernández, A. (2012). Matrix effects on the antimicrobial capacity of silver based nanocomposite absorbing materials. LWT - Food Science and Technology, 49, 333–338.

Lopez Rubio, A., Almenar, E., Hernandez Munoz, P., Lagaron, J., Catala, R., & Gavara, R. 2004. Overview of active polymer-based packaging technologies for food applications. Food Reviews International, 20, 357-387.

Lorenzo, J. M., & Gomez, M. (2012). Shelf life of fresh foal meat under MAP, overwrap and vacuum packaging conditions. Meat Science, 92, 610-618.

Lövenklev, M., Artin, I., Hagberg, O., Borch, E., Holst, E., & Ra˚dstro¨m, P. (2004). Quantitative interaction effects of carbon dioxide, sodium chloride, and sodium nitrite on neurotoxin gene expression in nonproteolytic *Clostridium botulinum* type B. Applied and Environmental Microbiology, 70, 2928–2934.

Lu, L.X., Cai Y., & Zheng, W. Z. (2011). Time temperature indicator based on lipase reaction diffusion. China patent CN201964968U.

Lu, L.X., Jia Z.Q., Cai Y. (2011). Microbial type time-temperature indicator for low-temperature circulation items. China patent CN102507576B.

Lund, M. N., Hviid, M. S., & Skibsted, L. H. (2007a). The combined effect of antioxidants and modified atmosphere packaging on protein and lipid oxidation in beef patties during chill storage. Meat Science, 76, 226-233.

Lund, M. N., Lametsch, R., Hviid, M. S., Jensen, O. N., & Skibsted, L. H. (2007b). High-oxygen packaging atmosphere influences protein oxidation and tenderness of porcine longissimus dorsi during chill storage. Meat Science, 77, 295-303.

Luño, M., Beltrán, J. A., & Roncalés, P. (1998). Shelf-life extension and colour stabilisation of beef packaged in a low $O_2$ atmosphere containing CO: Loin steaks and ground meat. Meat Science, 48, 75-84.

Luño, M., Roncalés, P., Djenane, D., & Beltrán, J. A. (2000). Beef shelf life in low $O_2$ and high $CO_2$ atmospheres containing different low CO concentrations. Meat Science, 55, 413-419.

Mach, N., Bach, A., Velarde, A., Devant, M. (2008). Association between animal, transportation, slaughterhouse practices, and meat pH in beef. Meat Science, 78, 232–238.

Macquarrie, R. (2005). Edible film formulation. US20050181020 A1.

Macquarrie, R. (2012). Vegetable casing film and method for production of tubular sausage casings. EP2482668 A1.

Macquarrie, R. (2014). Edible film compositions for processing of meat products. US 8728561 B2.

Macquarrie, R., Schupp, K., Taylor, P. (2004). Containing konjac and/or gellan gum; overcoming thermo-reversibility of carrageenan gel; nondisintegrating when exposed to hot or boiling water. US6730340 B1.

Maftoonazad, N., Badii, F., Shahamirian, M. (2013). Recent innovations in the area of edible films and coatings. Recent Patents on Food, Nutrition & Agriculture, 5(3), 201-213.

Mahalik, N.P., Nambiar, A.N. (2010). Trends in food packaging and manufacturing systems and technology. Trends in Food Science & Technology, 21(3), 117–128.

Mancini, R. A., & Hunt, M. C. (2005). Current research in meat color. Meat Science, 71, 100-121.

Mancini, R. A., Suman, S. P., Konda, M. K., & Ramanathan, R. (2009). Effect of carbon monoxide packaging and lactate enhancement on the color stability of beef steaks stored at 1 degrees C for 9 days. Meat Science, 81, 71-76.

Mancini, R., Hunt, M., Hachmeister, K., Kropf, D., & Johnson, D. (2005). Exclusion of oxygen from modified atmosphere packages limits beef rib and lumbar vertebrae marrow discoloration during display and storage. Meat Science, 69, 493-500.

Manthou V, Vlachopoulou M. (2001). Bar-code technology for inventory and marketing management systems: A model for its development and implementation. International Journal of Product Economics, 71(1-3):157–64.

Marcos, B., Sárraga, C., Castellari, M., Kappen, F., Schennink, G., Arnau, J. (2014). Development of biodegradable films with antioxidant properties based on polyesters containing a-tocopherol and olive leaf extract for food packaging applications. Food Packaging and Shelf-life, 1(2), 140-150.

Marras, S. I., Kladi, K. P., Tsivintzelis, I., Zuburtikudis, I., & Panayiotou, C. (2008). Biodegradable polymer nanocomposites: the role of nanoclays on the thermomechanical characteristics and the electrospun fibrous structure. Acta Biomaterialia, 4(3), 756–765.

Marsh, K., & Bugusu, B. (2007). Food packaging-roles, materials, and environmental issues. Journal of Food Science, 72, R39-55.

Mastromatteo, M., Incoronato, A. L., Conte, A., & Del Nobile, M. A. (2011). Shelf life of reduced pork back-fat content sausages as affected by antimicrobial compounds and modified atmosphere packaging. International Journal of Food Microbiology, 150, 1-7.

Maté, J.I., Krochta, J.M. 1997. Whey protein and acetylated monoglyceride edible coatings: effect on the rancidity process of walnuts. Journal of Agricultural and Food Chemistry, 45 (7), 2509–2513.

Mbhele, Z. H., Salemane, M. G., van Sittert, C. G. C. E., Nedeljkovic, J. M., Djokovic, V., & Luyt, A. S. (2003). Fabrication and characterization of silver–polyvinyl alcohol nanocomposites. Chemistry of Materials, 15(26), 5019–5024.

McDonald, N. 2013. Standards, regulations and testing of biodegradable polymers. Organic Waste Systems, Inc. Presentation at GPEC Conference, March 6, 2013, London, Ontario.

McMillin, K. W. (1996). Initiation of oxidative processes in muscle foods. In: Proceedings 49th reciprocal meat conference, 9–12 June 1996. Provo, Utah, USA, pp 53-64

McMillin, K. W. (2008). Where is MAP Going? A review and future potential of modified atmosphere packaging for meat. Meat Science, 80, 43–65

Meischen, H., Huffman, D., & Davis, G. Branded beef-product of tomorrow today. In: Proceedings of the Reciprocal Meat Conference, 1987. pp 37-46

Melero, B., Diez, A. M., Rajkovic, A., Jaime, I., & Rovira, J. (2012). Behaviour of non-stressed and stressed *Listeria monocytogenes* and *Campylobacter jejuni* cells on fresh chicken burger meat packaged under modified atmosphere and inoculated with protective culture. International Journal of Food Microbiology, 158, 107-112.

Mennecke, B., & Townsend, A. (2005). Radio frequency identification tagging as a mechanism of creating a viable producer's brand in the cattle industry. MATRIC (Midwest Agribusiness research and Information Center) research Paper 05-MRP 8. Available from http:// www.matric.iastate.edu.

Mensitieri, G., Di Maio, E., Buonocore, G. G., Nedi, I., Oliviero, M., Sansone, L., & Iannace, S. (2011). Processing and shelf life issues of selected food packaging materials and structures from renewable resources. Trends in Food Science & Technology, 22, 72-80.

Mihindukulasuriya, S.D.F. & Lim, L.-T. (2014). Nanotechnology development in food packaging: A review. Trends in Food Science & Technology, 40 149–167

Mize, J. A. (2005). Multicomponent package. US, US20070092610 A1.

Mohan, A.M. 2010. Biodegradable polymers market to grow at 13% through 2014. Packaging world.com. http://www.packworld.com/sustainability/strategy/biodegradable-polymers-market-grow-13-through-2014.

Mondry, H. (1996). Packaging systems for processed meat. In S. A. Taylor, A. Raimundo, M. Severini, & F. J.M. Smulders (Eds.), Meat quality and meat packaging. Utrecht, Holland: ECCEAMST (pp. 323–333).

Moorhead, S., & Bell, R. (1999). Psychrotrophic clostridia mediated gas and botulinal toxin production in vacuum-packed chilled meat. Letters in Applied Microbiology, 28, 108-112.

Moraru, C. I., Panchapakesan, C. P., Huang, Q., Takhistov, P., Liu, S., & Kokini, J. L. (2003). Nanotechnology: a new frontier in Food Science. Food Technology, 57, 24–29.

Mori, N., & Arai, I. (2004). Food product packaging film. US, US2004191368 A1

Mori, Y. (2010). Rules on food contact materials and articles in Japan, in Global legislation for Food Packaging Materials, R.V. Rinus Rijk, Editor. 2010, Wiley-VCH: Weinheim. p. 291-319.

Morones JR, Elechiguerra JL, Camacho A, Holt K, Kouri JB, Ramirez JT. (2005). The bactericidal effect of silver nanoparticles. Nanotechnology, 16, 2346–2353.

Morrissey, P. A., Sheehy, P. J. A., Galvin, K., Kerryh, J. P., & Buckleyh, D. J. (1998). Lipid stability in meat and meat products. Meat Science, 49, S73–S86.

Morsy, M.K., Khalaf, H.H., Sharoba, A.M., El-Tanahi, H.H., Cutte, C.N. (2014). Incorporation of Essential Oils and Nanoparticles in Pullulan Films to Control Foodborne Pathogens on Meat and Poultry Products. Journal of Food Science, 79(4), M675–M684.

Mousavi, A., Sarhavi, M., Lenk, A., & Fawcett, S. (2002). Tracking and traceability in the meat processing industry: a solution. *British Food Journal*, 104, 7–19.

Mullan, M., & McDowell, D. (2003) Modified atmosphere packaging. Food packaging technology. CRC, Boca Raton.

Müller, R.J. (2003). Biodegradability of polymers: regulations and methods for testing, Ch 12 in Biopolymers Volume 10 General Aspects and Special Applications. Ed. A. Steinbüchel, John Wiley & Sons, Ltd, Weinheim, Germany.

Muller, S. A. (1990). Packaging and Meat Quality. Canadian Institute of Food Science and Technology Journal, 23, 22-25.

Munro, I. C., Haighton, L. A., Lynch, B. S., & Tafazoli, S. (2009). Technological challenges of addressing new and more complex migrating products from novel food packaging materials. Food Additives and Contaminants, 26(12), 1534-1546.

Muppall, S.R., Kanatt, S.R., Chawl, S.P., Sharm, A. (2014). Carboxymethyl cellulose–polyvinyl alcohol films with clove oil for active packaging of ground chicken meat. Food Packaging and Shelf Life, 2(2), 51–58.

Murphy, K. M., O'Grady, M. N., & Kerry, J. P. (2013). Effect of varying the gas headspace to meat ratio on the quality and shelf-life of beef steaks packaged in high oxygen modified atmosphere packs. Meat Science, 94, 447-454.

Nielsen, L. E. (1967). Models for the permeability of filled polymer systems. Journal of Macromolecular Science Part A: Pure and Applied Chemistry, 1, 929–942

NLR (The National Law Review Co.). (2014). Nanotechnology in food production: FDA finalizes guidance on manufacturing process changes for food additives. http://www.natlawreview.com/article/nanotechnology-food-production-fda-finalizes-guidance-manufacturing-process-changes-. Posted on July 1, 2014.

Nørrung, B., Buncic, S. (2008). Microbial safety of meat in the European Union. Meat Science 78, 14–24

Nur Hanani, Z.A., Roos, Y.H., Kerry, J.P. (2014). Use and application of gelatin as potential biodegradable packaging materials for food products. International Journal of Biological Macromolecules, 71, 94–102.

Ogiue, H., & Hanai, T. (2006) Film for packaging meat. JP, JP2008127035 A.

Oksman, K., Mathew, A. P., Bondeson, D., & Kvien, I. (2006). Manufacturing process of cellulose

whiskers/polylactic acid nanocomposites. Composites Science and Technology, 66, 2776–2784.

Oliveira, L. M., Sarantópoulos, C. I. G. L., Cunha, D. G., & Lemos, A. B. (2006). Thermoformed and thermoprocessable plastic packages for processed meat. Polímeros, 16, 202-210.

Ortolani, R., Sagratini, G., Sirocchi, V., Vittori, S. (2013). Material for packaging fresh food of animal origin inhibiting the development of biogenic amines. WO 2013084175 A1.

Oskam, G. (2006). Metal oxide nanoparticles: synthesis, characterization and application. Journal of Sol-Gel Science and Technology, 37, 161–164.

Owczarek-Fendor, A., Vermeulen, A., Van Bree, I., Eriksson, M., Lescouhier, S., De Smet, S., De Meulenaer, B., & Devlieghere, F. (2014). Effect of muscle, ageing time and modified atmosphere packaging conditions on the colour, oxidative and microbiological stability of packed beef. International Journal of Food Science & Technology, 49, 1090-1098.

Ozdemir, M., & Floros, J. D. (2004). Active food packaging technologies. Critical Reviews in Food Science and Nutrition, 44, 185-193.

Özogul, F., Polat, A., & Özogul, Y. (2004). The effects of modified atmosphere packaging and vacuum packaging on chemical, sensory and microbiological changes of sardines (*Sardina pilchardus*). Food Chemistry, 85, 49-57.

Paiva, L. B., Morales, A. R., & Diaz, F. R. V. (2008). Organoclays: properties preparation and applications. Applied Clay Science, 42, 8–24.

Paralikar, S. A., Simonsen, J., & Lombardi, J. (2008). Poly(vinyl alcohol)/cellulose nanocrystal barrier membranes. Journal of Membrane Science, 320, 248–258.

Park, H. M., Lee, W. K, Park, C. Y., Cho, W. J., & Ha, C. S. (2003). Environmentally friendly polymer hybrids: part I. Mechanical, thermal, and barrier properties of the thermoplastic starch/clay nanocomposites. Journal of Mater Science, 38, 909–915

Park, S., Hettiarachcht, N.S., Ju, Z.Y., Gennadios, A. (2002). Formation and properties of soy protein films and coatings. In: A Gennadios, ed. Protein-based films and coatings. Boca Raton, FL: CRC Press, pp 123–137.

Park, S.I, Daeschel, M.A., Zhao, Y. (2004). Functional properties of antimicrobial lysozyme-chitosan composite films. Journal of Food Science, 69, M215–221.

Parra, V., Viguera, J., Sanchez, J., Peinado, J., Esparrago, F., Gutierrez, J. I., & Andres, A. I. (2010). Modified atmosphere packaging and vacuum packaging for long period chilled storage of dry-cured Iberian ham. Meat Science, 84, 760-768.

Peelman, N., Ragaert, P., Vandemoortele, A., Verguldt, E., Meulenaer, B.D., Devlieghere, F. (2014). Use of biobased materials for modified atmosphere packaging of short and medium shelf-life food products. Innovative Food Science and Emerging Technologies, 26, 319–329.

Pennacchia, C., Ercolini, D., & Villani, F. (2011). Spoilage-related microbiota associated with chilled beef stored in air or vacuum pack. Food Microbiology, 28, 84-93.

Pereira de Abreu, D. A., Cruz, J. M. & Paseiro Losada, P. (2012). Active and intelligent packaging for the food industry. Food Reviews International, 28, 146–187.

Pereira De Abreu, D.A., Cruz, J.M., Losada, P.P. (2012). Active and intelligent packaging for the food industry. Food Reviews International, 28,146–187.

Petersson, L., Kvien, I., & Oksman, K. (2007). Structure and thermal properties of poly(lactic acid)/cellulose whiskers nanocomposite materials. Composites Science and Technology, 67, 2535–2544.

Petrou, S., Tsiraki, M., Giatrakou, V., & Savvaidis, I. N. (2012). Chitosan dipping or oregano oil treatments, singly or combined on modified atmosphere packaged chicken breast meat. International Journal of Food Microbiology, 156, 264-271.

Pierson, M. D., Smoot, L. A., & Robach, M. C. (1983). Nitrite, nitrite alternatives, and the control of clostridium botulinum in cured meats. Critical Reviews in Food Science and Nutrition17, 141–187.

Piringer, O. G. & Baner, A. L. (2000). Plastic packaging materials for food. Wiley VCH, Weinheim.

Pockat, G.R., Schell, T.A., Siegel, D.G., Nelson, K.P., Berbert, O.T. (2014). Myoglobin blooming agent containing shrink films, packages and methods for packaging. US 8668969 B2.

Podsiadlo, P., Choi, S. Y., Shim, B., Lee, J., Cuddihy, M., & Kotov, N. A. (2005). Molecularly engineered nanocomposites: layer-by-layer assembly of cellulose nanocrystals. Biomacromolecules, 6, 2914–2918.

Pointon, A., Jenson, I., Jordan, D., Vanderlinde, P., Slade, J, & Sumner, J. (2006). A risk profile of the Australian red meat industry: Approach and management. Food Control, 17, 712–718.

Porter, J., Ting, Y.-P. R., & Moul, T. D. (2003). Lamination for specialty meat packaging. US, US2003170409 A1.

Premanathan, M., Karthikeyan, K., Jeyasubramanian, K., & Manivannan, G. (2011). Selective toxicity of ZnO nanoparticles toward Gram-positive bacteria and cancer cells by apoptosis through lipid peroxidation. Nanomedicine, 7, 184–192.

Prince, T. A. (1989) Modified atmosphere packaging of horticultural commodities. Controlled/modified atmosphere/vacuum packaging of foods. Food & Nutrition Press, Trumbull, Connecticut.

Priolo, M. A. , Gamboa, D., Grunlan, J. C. (2010). Transparent clay–polymer nano brick wall assemblies with tailorable oxygen barrier. ACS Applied Mater Interfaces 2, 312–320

Puolanne, E., & Halonen, M. (2010). Theoretical aspects of water-holding in meat. Meat Science, 86, 151-165.

Qi, L. F., Xu, Z. R., Jiang, X., Hu, C., & Zou, X. (2004). Preparation and antibacterial activity of chitosan nanoparticles. Carbohydrate Research, 339, 2693–2700.

Qin, H., Zhao, C., Zhang, S., Chen, G., & Yang, M. (2003). Photooxidative degradation of polyethylene/montmorillonite nanocomposite. Polymer Degradation and Stability, 81, 497–500

Qin, Y.Y., Yang, J.Y., Lu, H.B., Wang, S.S., Yang, J., Yang, X.C., Chai, M., Li, L., Cao, J.X. (2013). Effect of chitosan film incorporated with tea polyphenol on quality and shelf life of pork meat patties. International Journal of Biological Macromolecules, 61, 312–316.

Quan, C. & Stevens, R. (1998). Protein Coupled Colorimetric Analyte Detectors. PCT International Patent Application WO 95/33991.

Quintavalla, S., & Vicini, L. (2002). Antimicrobial food packaging in meat industry. Meat Science, 62, 373–380.

Rakshit, M., Ramalingam, C. (2013). Gum acacia coating with garlic and cinnamon as an alternate, natural preservative for meat and fish. African Journal of Biotechnology, 12(4), 406-413.

Ramamoorthi, L., Toshkov, S., & Brewer, M. S. (2009). Effects of carbon monoxide-modified atmosphere packaging and irradiation on E. coli K12 survival and raw beef quality. Meat Science, 83, 358-365.

Rao, D. N. & Sachindra, N. M. (2002). Modified atmosphere and vacuum packaging of meat and poulty products. Food Reviews International, 18, 263–293

Rao, D. N., & Sachindra, N. M. (2002). Modified atmosphere and vacuum packaging of meat and poultry products. Food Reviews International, 18, 263-293.

Rasanayagam, V., & Sundaram, M. (2012). Plasma generation of CO for modified atmosphere packaging.US, US2012156340 A1.

REACH- Registration, Evaluation, Authorisation and Restriction of Chemicals, http://ec.europa.eu/enterprise/sectors/chemicals/reach/index_en.htm, accessed on 23/01/2015

Realini, C.E., Marcos, B. (2014). Active and intelligent packaging systems for a modern society. Meat Science, 98(3), 404–419.

Restuccia, D., Spizzirri, U. G., Parisi, O. I. et al. (2010).  New EU regulation aspects and global market of active and intelligent packaging for food industry applications. Food Control 21, 1425–1435

Rhim, J.W., Hong, S.I., Park, H.M., Ng, P.K.W. (2006). Preparation and characterization of chitosan-based nanocomposite films with antimicrobial activity. Journal of Agricultural and Food Chemistry, 54, 5814–5822

Rhim, J-W, Park, H-M., Ha, C-S. (2013). Bio-nanocomposites for food packaging applications. Progress in Polymer Science, 38, 1629–1652

Ripoll, G., Joy, M., & Munoz, F. (2011). Use of dietary vitamin E and selenium (Se) to increase the shelf life of modified atmosphere packaged light lamb meat. Meat Science, 87, 88-93.

Roberge, M., & Fredette, J.-P. (2009). Anti-leak meat pack, food packaging tray therefore, and associated methods. WO, WO2010063094 A1.

Robertson, G. L. (1993). Food packaging: principles and practice. Marcel Dekker, New York.

Robertson, G. L. (2005). Food packaging: Principles and practice. New York: CRC press.

Robertson, G. L. (2006). Food packaging: principles and practice. Food science and technology. Boca Raton: Taylor & Francis.

Robertson, G.L. (2013). Edible, biobased and biodegradable food packaging materials. Ch. 3 In "Food Packaging: Principles and Practice," 3rd ed., 49-90, CRC Press, Boca Raton, Fla.

Robertson, G.L. (2014). Biobased but not biodegradable. Food Technology, 68(6), 61–70.

Rogers, H. B., Brooks, J. C., Martin, J. N., Tittor, A., Miller, M. F., & Brashears, M. M. (2014). The impact of packaging system and temperature abuse on the shelf life characteristics of ground beef. Meat Science, 97, 1-10.

Rojas-Graü, M.A., Soliva-Fortuny, R., Martín-Belloso, O. (2009). Edible coatings to incorporate active ingredients to fresh-cut fruits: a review. Trends in Food Science & Technology, 20(10), 438–447.

Rooney, M. L. (2005). Oxygen-scavenging packaging. In J. H. Han (Ed.), Innovations in food packaging (pp. 123e137). San Diego, USA: Elsevier Academic Press.

Rosnes, J. T., Sivertsvik, M., & Skara, T. (2003) Combining MAP with other preservation techniques. In: Ahvenainen R (ed) Novel food packaging techniques. CRC, Boca Raton, Boston, New York, Washington, DC pp 228-301.

Roveda, C., & Capitani, S. (2006) Packaging process for fresh meat products, new fresh meat package obtainable thereby and twin lidding film suitable therefor. CA, CA2598404 A1.

Rubio, B., Martinez, B., Gonzalez-Fernandez, C., Garcia-Cachan, M. A., Rovira, J., & Jaime, I. (2007). Effect of modified atmosphere packaging on the microbiological and sensory quality on a dry cured beef product: "Cecina de leon". Meat Science, 75, 515-522.

Sanches-Silva. A., Costa, D., Albuquerque, T.G., Buonocore, G.G., Ramos, F., Castilho, M.C., Machado, A.V., Costa, H.S. (2014). Trends in the use of natural antioxidants in active food packaging: a review. Food Additives and Contaminants. Part A, Chemistry, Analysis, Control, Exposure and Risk Assessment. 31(3), 374–95.

Sánchez-Escalante, A., Djenane, D., Torrescano, G., Beltrán, J. A., & Roncalés, P. (2001). The effects of ascorbic acid, taurine, carnosine and rosemary powder on colour and lipid stability of beef patties packaged in modified atmosphere. Meat Science, 58, 421-429.

Sanchez-Garcia, M. D., & Lagaron, J. M. (2010). Novel clay based nanobiocomposites of biopolyesters with synergistic barrier to UV light. Journal of Applied Polymer Science, 118(1), 188–199.

Sanchez-Garcia, M. D., Gimenez, E., & Lagaron, J. M. (2008). Morphology and barrier properties of solvent cast composites of thermoplastic biopolymers and purified cellulose fibers. Carbohydrate Polymers, 71, 235–244.

Sanchez-Garcia, M. D., Lagaron, J. M., & Hoa, S. V. (2010). Effect of addition of carbon nanofibers and carbon nanotubes on properties of thermoplastic biopolymers. Composite Science and Technology, 70, 1095–1105.

Sanchez-Garcia, M. D., Lopez-Rubio, A. and Lagaron, J. M. (2010). Natural micro and nanobiocomposites with enhanced barrier properties and novel functionalities for food biopackaging applications. Trends in Food Science & Technology 21 528–536.

Sánchez-Ortega, I., García-Almendárez, B.E., Santos-López, E.M., Amaro-Reyes, A., Barboza-Corona, J.E., Regalado, C. (2014). Antimicrobial edible films and coatings for meat and meat products preservation. The Scientific World Journal, Volume 2014, Article ID 248935,

Sandhya (2010). Modified atmosphere packaging of fresh produce: Current status and future needs. LWT - Food Science and Technology, 43, 381-392.

Sandusky, C. L., Reynhout, G. S., & Jones, T. S. (2001). Method of extending color life of modified atmosphere packaged fresh red meat using labiatae plant extracts. WO, WO0189308 A2.

Ščetar, M., Kurek, M., Galić, K. (2010). Trends in meat and meat products packaging – a review. Croatian

Journal of Food Science and Technology, 2 (1), 32–48.

Sebranek, J. G., Hunt, M. C., Cornforth, D. P., & Brewer, M. S. (2006). Carbon monoxide packaging of fresh meat. Food Technology, 60, 184.

Sharma, V. K., Yngard, R. A., & Lin, Y. (2009). Silver nanoparticles: green synthesis and their antimicrobial activities. Advances in Colloid and Interface Science, 145, 83–96.

Siegel, D. (2011) An update on packaging fresh meat with nitrite containing film. Paper presented at the 64th Reciprocal Meat Conference, Kansas State University, June 22.

Siegel, D. G., & Nelson, K. P. (2010) A film that uses an oxide of nitrogen to create nitroxymyoglobin and maintain the red colour of fresh meat. NZ, NZ550224 A.

Siegel, D., Nelson, K.P. (2007). Packaging method that causes and maintains the preferred red color of fresh meat. US20070275134 A1.

Siegel, D., Nelson, K.P. (2012a). Packaging articles, films and methods that promote or preserve the desirable color of meat. US8110259 B2.

Siegel, D., Nelson, K.P. (2012b). Improved packaging method that causes and maintains the preferred red color of fresh meat. US8110259 B2.

Siegel, D.G., Nelson, K.P., Michaud, R.A. (2014). Webs with synergists that promote or preserve the desirable color of meat. US 8741402 B2.

Siegel, D.G., Nelson, K.P., Pockat, G.R., Schell, T.A., et al. (2013). Method for distributing a myoglobin-containing food product. US8545950 B2.

Silva-Weiss, M. Ih, Sobral, P. J. A., Gómez-Guillén, M. C., Bifani, V. (2013). Natural additives in bioactive edible films and coatings: functionality and applications in foods. Food Engineering Reviews, 5(4), 200-216.

Silvestre, C., Duraccio, D. & Cimmino, S. (2011). Food packaging based on polymer nanomaterials. Progress in Polymer Science, 36, 1766–1782.

Singh, R. P. (2000). Scientific principles of shelf-life evaluation. In: Man, D., & Jones, A. (eds). Shelf-life evaluation of food, 2nd ed. Gaithersburg, Md., Aspen Publishers. p 3-22

Sinha, R. S., & Okamoto, M. (2003). Polymer/layered silicate nanocomposites: a review from preparation to processing. Progress in Polymer Science 28, 1539–1641

Sivertsvik, M. (2000). Use of soluble gas stabilisation to extend shelf-life of fish. In: S.A. Georgakis (Ed.), Pro-ceedings of 29th WEFTA-meeting (pp. 79–91). Leptocarya, Pieria, Thessaloniki, Greece: Greek Society of Food Hygienists and Technologists (October 10–14, 1999).

Slinde, E., Egelandsdal, B. (2014). Meat treatment and preservation method. US20140227408 A1.

Smiddy, M., Papkovskaia, N., Papkovsky, D. B., & Kerry, J. P. (2002). Use of oxygen sensors for the non-destructive measurement of the oxygen content in modified atmosphere and vacuum packs of cooked chicken patties: impact of oxygen content on lipid oxidation. Food Research International, 35, 577–584.

Smiddy, M., Papkovsky, D. B., & Kerry, J. P. (2002). Evaluation of oxygen content in commercial modified atmosphere packs (MAP) of processed cooked meats. Food Research International, 35, 571–575.

Smolander, M. (2000). Freshness indicators for direct quality evaluation of packaged foods. In: International Conference on Active and Intelligent Packaging, Conference Proceedings, 7–8 September, pp. 1–16. Campden & Chorleywood Food Research Association Group, Chipping Campden, UK.

Smolander, M. (2003). The use of freshness indicators in packaging. In R. Ahvenainen (Ed.), Novel food packaging techniques (pp. 128–143). Cambridge, UK: Woodhead Publishing Ltd.

Smolander, M., & Chaudhry, Q. (2010). Nanotechnologies in Food Packaging. In Chaudhry, Q., Castle, L., Watkins, R. (eds). Nanotechnologies in Food. Cambridge : RSC Pub.

Smolander, M., Alakomi, H.-L., Ritvanen, T., Vainionpaa, J., & Ahvenainen, R. (2004). Monitoring of the quality of modified atmosphere packaged broiler chicken cuts stored in different temperature conditions: Time-temperature indicators as quality-indicating tools. Food Control 15, 217–29.

Smolander, M., Hurme, E., Latva-Kala, K., Luoma, T., Alakomi, H. L., & Ahvenainen, R. (2002). Myoglobin-

based indicators for the evaluation of freshness of unmarinated broiler cuts. Innovative Food Science and Emerging Technologies, 3, 279–288

Sofos, J. N. (2008). Challenges to meat safety in the 21st century. Meat Science 78, 3–13.

Sondi, I., Salopek-Sondi, B. (2004) Silver nanoparticles as antimicrobial agent: a case study on E. coli as a model for Gram-negative bacteria. Journal of Colloid Interface Science, 275, 177–182.

Song, I. H., Kim, W. J., Jo, C., Ahn, H. J., Kim, J. H., & Byun, M. W. (2003). Effect of Modified Atmosphere Packaging and Irradiation in Combination on Content of Nitrosamines in Cooked Pork Sausage. Journal of Food Protection, 66, 1090-1094.

Sørheim, O., Aune, T., & Nesbakken, T. (1997). Technological, hygienic and toxicological aspects of carbon monoxide used in modified-atmosphere packaging of meat. Trends in Food Science & Technology, 8, 307-312.

Sørheim, O., Nissen, H., & Nesbakken, T. (1999). The storage life of beef and pork packaged in an atmosphere with low carbon monoxide and high carbon dioxide. Meat Science, 52, 157-164.

Sørheim, O., Ofstad, R., & Lea, P. (2004). Effects of carbon dioxide on yield, texture and microstructure of cooked ground beef. Meat Science, 67, 231-236.

Sorrentino, A., Gorrasi, G. and Vittoria, V. (2007). Potential perspectives of bio-nanocomposites for food packaging applications Trends in Food Science & Technology, 18, 84-95.

Spencer, K. C. (1994). Method of preserving foods using noble gases. US, US6342261 B1.

Speranza, B., Corbo, M. R., Conte, A., Sinigaglia, M., & Del Nobile, M. A. (2009). Microbiological and sensorial quality assessment of ready-to-cook seafood products packaged under modified atmosphere. Journal of Food Science, 74, M473-478.

Stasiewicz, M., Lipiński, K., & Cierach, M. (2012). Quality of meat products packaged and stored under vacuum and modified atmosphere conditions. Journal of Food Science and Technology, 1-8.

Stolzenhoff, H. (2014). Method for producing a marked meat product. US20140154360 A1.

Stuchell, Y.M., Krochta, J.M. (1995). Edible coatings on frozen king salmon: effect of whey protein isolate and acetylated monoglycerides on moisture loss and lipid oxidation. Journal of Food Science, 60(1), 28-31.

Suman, S. P., Mancini, R. A., Joseph, P., Ramanathan, R., Konda, M. K., Dady, G., Naveena, B. M., & Lopez-Lopez, I. (2010). Color-stabilizing effect of lactate on ground beef is packaging-dependent. Meat Science, 84, 329-333.

Suman, S. P., Mancini, R. A., Ramanathan, R., & Konda, M. R. (2009). Effect of lactate-enhancement, modified atmosphere packaging, and muscle source on the internal cooked colour of beef steaks. Meat Science, 81, 664-670.

Sumimoto, M. (2013). Requirements for Food Packaging and Legislation in Japan. http://www.tikzn.co.za/Libraries/JETRO_presentations_2013/03_Requirements_for_Food_Packaging_and_Legislation_in_Japan.sflb.ashx access on 23/01/2015

Summerfield, J. W., Holst, E. J., & Nathan, R. S. (2011) Fresh meat color in vacuum packaged or modified atmosphere packaged fresh meat products. WO, WO2012016153 A1.

Sumner, J., Ross, T., Jenson, I., Pointon, A. (2005). A risk microbiological profile of the Australian red meat industry: Risk ratings of hazard–product pairings. International Journal of Food Microbiology 105, 221– 232

Sun, X.D., & Holley, R.A. (2012). Antimicrobial and antioxidative strategies to reduce pathogens and extend the shelf life of fresh red meats. Comprehensive Reviews in Food Science and Food Safety, 11(4), 340–354.

Sun, Y.E., Wang, W., Qin, W.W., Chen, W. (2013). Method for refreshing preserved pork by using edible composite antibacterial film. CN102487988 B.

Sung, S.Y., Sin, L.T., Tee, T.T., Bee, S.T., Rahmat, A.R., Rahman, W.A.W.A., Tan, A.C., Vikhraman, M. (2013). Antimicrobial agents for food packaging applications. Trends in Food Science & Technology, 33(2), 110–123.

Sung, S.Y., Sin, L.T., Tee, T.T., Bee, S.T., Rahmat, A.R., Rahman, W.A.W.A. (2014). Control of bacteria growth on ready-to-eat beef loaves by antimicrobial plastic packaging incorporated with garlic oil. Food Control, 39, 214-221.

Suppakul, P., Miltz, J., Sonneveld, K., & Bigger, S. W. (2003). Active packaging technologies with an emphasis on antimicrobial packaging and its applications. Journal of Food Science, 68, 408-420.

Swedberg, C. (2006). Beef tracking, the RFID way. RFID Journal, http://www.rfidjournal.com/articles/pdf?2845 (access on 7/10/2014)

Talebian, N., Nilforoushan, M. R., & Zargar, E. B. (2011). Enhanced antibacterial performance of hybrid semiconductor nanomaterials: ZnO/SnO$_2$ nanocomposite thin films. Applied Surface Science, 258(1), 547–555.

Tankhiwale, R., & Bajpai, S. K. (2012). Preparation, characterization and antibacterial applications of ZnO-nanoparticles coated polyethylene films for food packaging. Colloids and Surfaces, B: Biointerfaces, 90, 16–20.

Taoukis, P. S., & Labuza, T. P. (1989). Applicability of time temperature indicators as shelf-life monitors of food products. Journal of Food Science, 54, 783–788.

Taoukis, P. S., & Labuza, T. P. (2003). Time-temperature indicators (TTIs). In: Ahvenainen, R. (eds). Novel food packaging techniques. Cambridge U.K.: Woodhead Publishing Limited. p 103-126.

Taylor, A. A. & Shaw, B. G. (1977). The effect of meat pH and package permeability on putrefaction and greening in vacuum packed beef. Journal of Food Technology, 12, 515–521.

Taylor, S. (1994). Meat packaging research and development in the UK. Packaging Technology and Science, 7, 61-63.

The Commission of the European Communities. (2004). Regulation (EC) No. 1935/2004 of the European Parliament and of the Council of 27 October 2004 on materials and articles intended to come into contact with food and repealing Directives 80/590/EEC and 89/109/EEC. Official Journal of the European Union, 2004, L338/4.

Thostenson, E. T., Li, C., & Chou, T.-W. (2005). Nanocomposites in context. Composites Science and Technology, 65, 491–516.

Tian, F., Decker, E. A., & Goddard, J.M. 2013. Controlling lipid oxidation of food by active packaging technologies. Food and Function, 4(5), 669–680.

Topps, C. J. (2011). Processing and packaging meat without using highly absorbent material. US2014030392 A1.

Tsigarida, E., Boziaris, I.S., Nychas, G.-J.E. (2003). Bacterial synergism or antagonism in a gel cassette system. Applied Environmental Microbiology, 69, 7204–7209.

Turgis, M., Han, J., Borsa, J., & Lacroix, M. (2008). Combined effect of natural essential oils, modified atmosphere packaging, and gamma radiation on the microbial growth on ground beef. Journal of Food Protection, 71, 1237-1243.

Ünalan, I.U., Korel, F., Yemenicioğlu, A. (2011). Active packaging of ground beef patties by edible zein films incorporated with partially purified lysozyme and Na$_2$EDTA. International Journal of Food Science and Technology, 46(6), 1289–1295.

Uniform Code Council. (2014). GS1 DataBar Family. Available from: http://www.gs1us.org/resources/standards/barcodes/gs1-databar-family. Accessed 6 October 2014. Uniform Code Council. Lawrenceville, N.J.

Uskokovic, V. (2007). Nanotechnologies: what we do not know. Technology in Society, 29, 43–61.

Van, D. B. A. T. (2003). Process and polymer films for fresh meat packaging. US, US6581359 B1

Vargas, M., Pastor, C., Chiralt, A., McClements, D.J., González-Martínez, C. (2008). Recent advances in edible coatings for fresh and minimally processed fruits. Critical Reviews in Food Science and Nutrition, 48(6), 496-511.

Venturini, A. C., Faria, J. A. F., Olinda, R. A., & Contreras-Castillo, C. J. (2014). Shelf life of fresh beef stored in master packages with carbon monoxide and high levels of carbon dioxide. Packaging Technology and Science, 27, 29-35.

Vergara, H., & Gallego, L. (2001). Effects of gas composition in modified atmosphere packaging on the meat quality of Spanish Manchega lamb. Journal of the Science of Food and Agriculture, 81, 1353-1357.

Vermeiren, L., Devlieghere, F., van Beest, M., de Kruijf, N., & Debevere, J. (1999). Developments in the active packaging of foods. Trends in Food Science and Technology, 10, 77–86.

Versteylen, S., Riehle, L.A. (2014). Absorbent pads for food packaging. CA 2717873 C.

Wang, Q., Xu, W.J., Jiang, J. L., Liu, H.L. (2013). Internet-of-Things-oriented manufacturing technique for intelligent packages. China patent CN103208018A

Wang, S., Kuang, X., Li, B., Wu, X., Huang, T. (2013). Physical properties and antimicrobial activity of chilled meat pads containing sodium carboxymethyl cellulose. Journal of Applied Polymer Science, 127(1), 612–619.

Wang, Y., Zhang, Q., Zhang, C., & Li, P. (2012). Characterisation and cooperative antimicrobial properties of chitosan/nano-ZnO composite nanofibrous membranes. Food Chemistry, 132, 419–427.

Want R. (2004). RFID: A key to automating everything. Scientific American 290(1):56–65.

Watthanaphanit, A., Supaphol, P., Tamura, H., Tokura, S., & Rujiravanit, R. (2010). Wet-spun alginate/chitosan whiskers nanocomposite fibers: preparation, characterization and release characteristic of the whiskers. Carbohydrate Polymers, 79, 738–746.

Weerasinghe, S., Williams, J.B., Mukherjee, D., Tidwell, D.K., Chang, S., Haque, Z.U. 2013. Quality and sensory characteristics of cubed beef steak dipped in edible protective solutions of thermized cheddar whey. Journal of Food Quality, 36(2), 77–90.

Weiss, J., Takhistov, P., & McClements, D. J. (2006). Functional materials in food nanotechnology. Journal of Food Science, 71, R107–R116.

Wessel, R. (2007). Chill-On develops prototype RFID-enabled Time-Temperature Indicator, RFID Journal, http://www.rfidjournal.com/articles/pdf?3749, accessed on 22 October 2014.

Wiley, B., Sun, Y., Mayers, B., & Xia, Y. (2005). Shape-controlled synthesis of metal nanostructures: the case of silver. Chemistry – A European Journal, 11(2), 454–463.

Wilkinson, B. H., Janz, J. A., Morel, P. C., Purchas, R. W., & Hendriks, W. H. (2006). The effect of modified atmosphere packaging with carbon monoxide on the storage quality of master-packaged fresh pork. Meat Science, 73, 605-610.

Wolfe, S.K. (1980). Use of CO- and $CO_2$-enriched atmospheres for meats, fish, and produce. Food Technology, 34 (S3), 55–58.

Woraprayotea, W., Kingchab, Y., Amonphanpokinc, P., Kruenatec, J., Zendod, T., Sonomotod, K., Benjakula, S., Visessanguan, W. (2013). Anti-listeria activity of poly(lactic acid)/sawdust particle biocomposite film impregnated with pediocin PA-1/AcH and its use in raw sliced pork. International Journal of Food Microbiology, 167(2) 229–235.

Wu, T., Zivanovic, S., Draughon, F. A., Conway, W. S., & Sams, C. E. (2005). Physicochemical properties and bioactivity of fungal chitin and chitosan. Journal of Agricultural and Food Chemistry, 53, 3888–3894.

Wu, Y., Weller, C., Hamouz, F., Cuppett, S.L., Schnepf, M. (2002). Development and application of multicomponent edible coatings and films: a review. Advances in Food and Nutrition Research, 44, 347-394.

Xing, Y., Li, X., Zhang, L., Xu, Q., Che, Z., Li, W., et al. (2012). Effect of TiO2 nanoparticles on the antibacterial and physical properties of polyethylene-based film. Progress in Organic Coatings, 73, 219–224.

Xiong, Y. L., Lou, X., Harmon, R. J., Wang, C., & Moody, W. G. (2000). Salt- and pyrophosphate- induced structural changes in myofibrils from chicken red and white muscles. Journal of the Science of Food and Agriculture, 80, 1176-1182.

Yadav, T. & Vecoven, A. (2005). Silver comprising nanoparticles and related nanotechnology. US patent US 20050008861 A1.

Yam, K. L., Takhistov, P. T., & Miltz, J. (2005). Intelligent packaging: concepts and applications. Journal of Food Science, 70, R1–R10.

Yang M., Zhang, Z., Ye, L., Cui, Z., Zhang Q. (2005). Method for preparing nano-antibacterial fresh-keeping

plastic films. China patent CN 1195790 C.

Ye, K., Wang, H., Zhang, X., Jiang, Y., Xu, X., & Zhou, G. (2013). Development and validation of a molecular predictive model to describe the growth of Listeria monocytogenes in vacuum-packaged chilled pork. Food Control, 32, 246-254.

Yingyuad, S., Ruamsin, S., Reekprkhon, D., Douglas, S., Pongamphai, S., & Siripatrawan, U. 2006. Effect of chitosan coating and vacuum packaging on the quality of refrigerated grilled pork. Packaging Technology and Science, 19, 149–157.

Youssef, A. M. (2013). Polymer nanocomposites as a new trend for packaging applications. Polymer-Plastics Technology and Engineering, 52, 635–660.

Zakrys, P. I., O'Sullivan, M. G., Allen, P., & Kerry, J. P. (2009). Consumer acceptability and physiochemical characteristics of modified atmosphere packed beef steaks. Meat Science, 81, 720-725.

Zakrys-Waliwander, P. I., O'Sullivan, M. G., O'Neill, E. E., & Kerry, J. P. (2012). The effects of high oxygen modified atmosphere packaging on protein oxidation of bovine M. *longissimus dorsi* muscle during chilled storage. Food Chemistry, 131, 527-532.

Zhai, R. C. (2010). Intelligent packaging bottle with voice advertisement. China patent CN201784843U

Zhang, Q. Q., Han, Y. Q., Cao, J. X., Xu, X. L., Zhou, G. H., & Zhang, W. Y. (2012). The spoilage of air-packaged broiler meat during storage at normal and fluctuating storage temperatures. Poultry Science, 91, 208-214.

Zhao, L. M., Shi, L. E., Zhang, Z. L., Chen, J. M., Shi, D. D., Yang, J., et al. (2011). Preparation and application of chitosan nanoparticles and nanofibers. Brazilian Journal of Chemical Engineering, 28, 353–362.

Zhao, Y., Lian, Z, and Yue, J. (2013). Recent development in food Packaging, a review. Journal of Chinese Institute of Food Science and Technology, 13(4), 1-10.

Zhao, Y., Simonsen, J., Cavender, G., Jung, J., Fuchigami, L.H. (2014). Nano-cellulose coatings to prevent damage in foodstuffs. US 20140272013 A1.

Zhou, G. H., Xu, X. L., & Liu, Y. (2010). Preservation technologies for fresh meat - a review. Meat Science, 86, 119-128.

Zhou, G.H., Xu, X.L., Liu, Y. (2010). Preservation technologies for fresh meat – A review. Meat Science, 86 119–128.

Zhou, J., Wang, L., Wang, Q., Feng, Z., Tian, F., Fan, X., Pan, Z., Ren, L., Tong, J. (2013). Method for preparing chitosan-based composite preservative film or coating. CN 103275358 A.

Zhou, Q.H., Li, W., Tang, J.X., Hu, C.S., Deng, J. (2012). Active packaging film for chilled meat and preparation method of the active packaging film. CN 102604292 A.

Zhu, C. (2005). High barrier, degradable film and its manufacturing method. China patent CN 1640649 A.

Zimoch-Korzycka, A., Jarmoluk, A. (2014). The use of chitosan, lysozyme, and the nano-silver as antimicrobial ingredients of edible protective hydrosols applied into the surface of meat. Journal of Food Science and Technology, DOI: 10.1007/s13197-014-1645-7.