Innovations in Meat Packaging Technology: A Review

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Prepared by:	Dr David Hopkins NSW DPI Dr Benjamin Holman NSW DPI Dr Joseph Kerry UCC
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Executive Summary

Meat packaging operates across three levels (primary, secondary and tertiary) all of which must innovate to match consumer packaging requirements and operate within an increasingly globalised market.

There are many demands (i.e. safety, product quality, traceability, convenience, shelf-life preservation, environmental, integrity assurance) forcing innovation in meat packaging, and prompting the adoption of smart packaging. Consumer pressure, rather than from the processor, will more often result in adoption of novel packaging.

Smart Packaging can be defined by three distinctive categories:

1. Active packaging – this describes technologies that directly manipulate the environment of the packaged contents to promote preservation of quality and safety characteristics (i.e. emitters and scavengers can be embedded into packaging materials or be provided as inserts which alter package gas, moisture or microbial content, or packaged product biochemical properties).

2. Intelligent packaging – this employs sensing technologies to quantify packaged product status, in terms of quality, freshness, integrity or physical location (i.e. radio frequency identification tags can relay scrutinise product quality as determined using sensors, from a remote location).

3. Consumer interactive technologies – these must be actively utilised by consumers to enhance convenience and knowledge of the packaged product (i.e. smart oven instructions included on the packaging to allow automated cooking, or rapid communication (RC) coding on packs to better inform consumers of the contents).

There already exists many inventions with applications to smart packaging (evident in patents), albeit often meat packaging functions were identified post-development (e.g. innovations in microbial sensors for medical applications can be used as an intelligent packaging option).

These patented technologies are more often singular in function and are yet to be validated for smart meat packaging. Combining technologies into a multi-functional product could improve information synthesis and cost-effectiveness of application, and testing within a meat packaging context could bolster stakeholder confidence and further adoption and improvement.

The cost effectiveness of any smart packaging technology (as determined per perceived benefits and profit margins or economic exchanges) is a major consideration influencing widespread adoption.

To understand the feasibility of smart packaging adoption, several questions must be addressed:

- What are the legislative, environmental and system usage considerations?

- Which stakeholder is prompting adoption (i.e. consumer convenience driven change) and to what extent should collected information or the presence of smart packaging technology be shared?

- Can the smart packaging technology (both existing and theoretical) provide valid and valuable improvements or information as to product status?

- Is there scope to combine multiple technologies into a single unit or innovation?

- Would improvements to traditional or holistic packaging, processing and production systems have greater benefits for packaged meat product quality, safety and preservation than smart packaging option?

Assuming appropriate investment to facilitate the investigation of these queries; smart packaging offers effective advantages to all participants involved with meat processing, retailing and consuming. Consequently it appears likely that smart packaging technologies for muscle-based food products will become more common-place in the years to come.

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1.0 Background

The primary function of meat product packaging is to protect against oxygen (O_2), water vapour, UV light and both chemical and microbial interferences, with an ideal packaging achieving these while maintaining optimal product quality and viability over prolonged durations. Unfortunately meat packaging is not infallible; with the FAO (2011) showing approximately 5% of total meat wastage occurs during processing and packaging phases, and Abelson, Forbes, & Hall (2006) reporting that up to 5.4 million cases of food borne illness occurs annually in Australia. These economic and health considerations stimulate effort towards developments in meat packaging. The predominant focus in meat packaging research is on 'smart packaging' which differs from traditional packaging in terms of its designed interactions with contents and/or its surrounding environment as opposed to solely functioning as an inert container. Smart packaging can be categorised into three basic types:

1. **Intelligent Packaging** - this involves the inclusion of sensory instrumentation into/onto packaging to measure and report the status of its contents. Research into this packaging type has led to the development of sensors that report product integrity and biosecurity (Hurme, 2003), product freshness using chemical (Dainty, 1996) and microbial (Smolander & Ahvenainen, 2003) markers, and product quality via temperature logging, pH and gas accumulation analysis (Kuswandi, Wicaksono, Abdullah, Heng, & Ahmad, 2011).

2. **Active Packaging** - this is designed to interact with its contents dependent on shifts in content status. This can be achieved by imbedding antimicrobial properties into packaging materials that inhibit spoilage bacterium proliferation (Ouattara, Simard, Piette, Bégin, & Holley, 2000), antioxidant inference using O_2 scavengers (Pereira de Abreu, Maroto, Villalba Rodríguez, & Cruz, 2012b), or moisture management by removing meat product drip and hence suppressing microbial growth potential (Kerry, O'Grady, & Hogan, 2006).

3. **Preservative Packaging** – this aims to prolong the longevity of the packaged contents and includes modified atmosphere packaging (MAP). MAP involves the replacement of the air surrounding a meat product with a formulated gas mix containing principally inert gases (Kerry, et al., 2006). These are designed to limit meat spoilage and oxidation, and doing so extends product shelf-life. Vacuum packaging (VP) offers another means to achieve this without the negative effects of some inert gases on quality and combinations of MAP and VP are also available. In this area skin packaging is a more recent development that is gaining widespread acceptance.

Meat packaging technology has evolved with emerging technology and increased market demands. For instance, research developing specialised coatings and surface treatments that release bioactive molecules (i.e. antioxidants) within packaged environments is being actively pursued (Kerry, 2012, 2014). Edible packaging is also being explored as a practical

method of meeting consumer environmental and aesthetical demands (Kerry, et al., 2006). However, as with all novel technology, improved knowledge is necessary to ensure it is feasible, is validated and then is applied. Another essential consideration revolves around intellectual property, with many domestic and international patents held on many aspects of meat packaging. These include novel packaging materials and quality sensors, and present much information on the direction of packaging innovation. It is important, however, to ensure any future meat packaging advancement does not infringe on existing patents.

1.1 Project Scope

This brief background provides a glimpse into the diversity and breath of research currently applied towards meat packaging and investment into related patents. It emphasises the benefits which would be derived from the culmination of this existing knowledge into a single report.

2.0 Project Objectives

The project aimed to outline current and future trends in meat packaging technology, with a focus on smart packaging advances in product quality preservation and monitoring, by reviewing available scientific literature and relevant national or international patents.

The projected immediate outcomes from the project were:

- Successful submission to a peer reviewed journal;

- A workshop presented by key researchers summarising project findings to relevant stakeholders; and

- Development of an all-inclusive final report which defines meat packaging technology and, describes scientific research paucities and available patent gaps where investment would best aid meat packaging advancement and avoid patent infringement.

3.0 Methodology

The listed authors scrutinised and amalgamated information sourced from peer-reviewed scientific publications, industry products and reports, patent submissions, and consulted both industry and scientific experts in the construction of this report.

The conduct of the 'Innovations in Meat Packaging Technology Workshop' was achieved with assistance from AMPC Events, NSW Department of Primary Industries, and University College Cork.

4.0 Review of Literature

Food packaging is indispensable in the world in which we live today and is probably the greatest of all of the technologies available to us to ensure food preservation and product shelf-life. This review serves to highlight how smart packaging technologies have been used, are being used or have the potential of being used to further enhance muscle-based food product safety and physicochemical properties; provide in- or on-package indication of products status; or provide new and cleverer means by which consumers can interact with muscle-based food products. All of this permits muscle-based food products to be available with enhanced convenience and safety beyond that provided by the conventional primary food packaging systems.

4.1 Introduction

There is no official definition of smart packaging, but consensus recognises it as packaging that goes beyond the use of simple packaging materials combined with traditional printed features – for instance, alphanumeric, graphics or simple barcodes (Kerry & Butler, 2008a). This relatively new form of packaging has been classified in many ways – 'active', 'intelligent', 'diagnostic', 'functional' and 'enhanced'. The authors of this review, however, prefer to use the term 'smart' as it is a more encompassing term and one which is sympathetic to the great number of technologies that are covered under these other more specific headings. Furthermore, the term 'smart' provides the scope for other yet undeveloped technologies which may be included in the future under this banner with ease.

In the hierarchical order of packaging, we have primary, secondary and tertiary packaging which relate to sales, collation/handling and transport of goods, respectively. Smart packaging technologies can be applied in different ways, and for different reasons, to all three of these forms of packaging and yet no packaging level has been described for smart packaging entities. Consequently, we are left with a situation where a plethora of terms are used to describe various technologies which have a number of primary features in common; they must be applied to, operate and support all conventional packaging materials and primary, secondary and tertiary packaging systems. In the University College Cork (Ireland) packaging group, all of the packaging materials and formats utilised in primary, secondary and tertiary packaging are defined as 'first level packaging', while smart packaging is described as 'second level packaging'. For the purposes of this review, this is how these forms of packaging will be hence forth described.

It is important to point out at this juncture that this review builds on relatively recent reviews on the use of smart packaging technologies as applied specifically to conventionally packaged muscle-based foods (meat, poultry and seafood) and include several reports by Kerry, et al. (2006), Coma (2008), Hogan and Kerry (2008), O'Grady and Kerry (2008), Pacquit, Crowley, and Diamond (2008), (McMillian & Belcher, 2012), Kerry (2012), Kerry (2014), and Realini and Marcos (2014).

The fundamental aspects of all packaging materials is that in an economical manner, they must play some, or all roles, in containing, protecting, preserving, informing (throughout the entire distribution process from point of manufacture to point of consumer usage) and providing convenience (at many different levels), while acknowledging the constraints placed upon their usage from both legal and environmental perspectives. As these fundamental principles apply to all forms of packaging materials and systems to varying degrees, it follows that irrespective of the specific level at which the packaging is industrially applied, all must conform to these same principles (Cruz-Romero & Kerry, 2008).

4.2 Growing Demands of Current Commercial Packaging Systems for Muscle-based Food Productions

Modern day manufacture of muscle-based food products place demands on product packing systems that far exceed those used for similar products over the past two decades. It is envisaged that such demands will continue to evolve and it will be necessary for packaging technologies to keep pace and facilitate the process of bringing new and improved muscle-based products to market. The modern day challenges to packaging of muscle-based products are likely to come from those areas presented in Table 1.

Table 1. Present and future challenges to muscle-based foods packaging

CHALLENGES
- Legislative, safety, quality and traceability demands
- Movement of goods to further and more distant markets
- Requirement for longer product shelf-lives
- Demands for convenience, easy preparation, easy use, ready to heat and eat etc.
- Enhanced nutritional and health promoting food and beverage products
- Price point quality demands in the face of rising food and product prices
- Environmental concerns and issues pertaining to packaging sustainability
- Food wastage
- Product authenticity and adulteration
- Tampering and bioterrorism
- Special concerns – pesticides, herbicides, growth hormones, prions etc.

Muscle-based food products, which comprise one sub-product food grouping within consumer goods that must be rapidly retailed, have always posed unique packaging challenges. This is expected to continue into the future as commodity value and shifting global demands increase. We now have greater movement of food products between global markets than ever before; with some products moving back and forth along

transport and distribution lines in order to manufacture a single marketable product. Seafood is a very good example of this, where shellfish can be harvested in one part of the globe, transported over large distances to be processed in another, only to return again to the point of origin for product finalisation and marketing. As muscle-based food product value increases and the logistics of product movement become more complex, evidential demands by the market to demonstrate product quality, shelf-life, nutritional status and safety will be required. With respect to food safety, one can clearly see how various global food regulatory authorities have operated in recent years to enhance food safety issues; all of which has been underpinned by the demand for implementation of traceability systems. Furthermore, the necessity for such systems has been made even more apparent by the 2013/2014 horsemeat adulteration of beef products' scandal which occurred throughout Europe. Not alone does this example support the need for enhanced and efficient traceability systems, but points to other issues such as product authenticity – to combat non-authentic duplication and product pirating. While often such practices are associated with lower socio-economic regions of the globe, clearly, the horsemeat scandal clearly demonstrates otherwise. In any event, such practices ultimately lead, and have led, to the erosion of product value, brand and equity. For products such as these, issues pertaining to product tampering are of the utmost importance as the potential interference of product raises all manner of issues with respect to product purity, hygiene, and safety.

Packaging plays a pivotal role in providing consumers with convenience. Packaged product convenience is provided at numerous levels, such as; information provided on packs, retail suitability and stacking format for products, consumer handling, storage and user features and provision of packaging materials which assists in reusing, recycling, composting or ultimate disposal of post-consumer packaging waste. While convenience features have been widely adopted in muscle-based packaged products, especially value-added and processed products (i.e. easy open, easy close, microwave-friendly features etc.); the application of convenience measures to muscle-based food products have been limited, especially for fresh meat products. For example, consumers have become more aware about meat safety issues and yet, more distant and removed in terms of their knowledge of food production, and we have situations where consumers want meat products presented to them in packs that are easy peel and which allows meat to be placed into a cooking utensil without having to handle the raw product directly.

4.2.1 First Level Packaging for Application to Muscle-based Food Products

First level packaging for fresh meat, poultry and seafood is carried out to avoid contamination, delay microbial, chemical and biochemical spoilage, permit some enzymatic activity to improve tenderness (as in the case of fresh meat), reduce weight loss, and visually present the muscle-based product to the consumer in a format which enhances overall product appearance and meets consumer desires and expectations. When considering processed muscle-based products, factors such as dehydration, lipid oxidation, discoloration and loss of aroma must be taken into account (Mondry, 1996). Many muscle-based packaging systems currently exist within the retailing environment,

each with different attributes and applications. A broader list of considerations is presented in Table 2.

Table 2. Factors affecting the general deterioration of muscle-based food products

ISSUES PERTAINING TO PRODUCT DETERIORATION AND SPOILAGE
- Product appearance and colour
- Microbiological and hygiene status
- Chemical stability of product components
- Sensory attributes
- Moisture loss or gain
- Oxygen loss or gain
- Carbon dioxide loss or gain
- Odour loss or gain
- Packaging integrity and containment
- Product and package compatibility

The packaging systems used for muscle-based food products range from overwrapping for short-term chilled storage and/or retail display, to a diversity of specified MAP systems for longer-term chilled storage and/or retail display, to vacuum packaging applications, bulk-gas flushing or MAP systems using 100% carbon dioxide (CO_2) for long-term chilled storage.

Due to the diversity of product characteristics associated with muscle-based food products (i.e. meat, poultry and seafood) and basic packaging demands and applications, any packaging technologies offering to deliver more product and quality control in an economic and diverse manner would be favourably welcomed. This is what second level packaging exists to achieve.

4.2.2 Second Level Packaging for Application to Muscle-based Food Products

As outlined above, smart packaging is a broad term encompassing a range of relatively new packaging concepts, most of which can be placed in one of three principle categories; active packaging, intelligent packaging and consumer interactive packaging (Kerry, 2014).

Active packaging refers to the incorporation of certain additives into packaging systems (whether loose within the pack, attached to the inside of packaging materials or incorporated within the packaging materials themselves) with the aim of maintaining or extending product quality and shelf-life. Packaging may be termed active when it performs some desired role in food preservation in addition to providing an inert barrier to external conditions (Hutton, 2003). Active packaging has been defined as packaging which 'changes the condition of the packed food to extend shelf-life or to improve safety or sensory properties, while maintaining the quality of packaged food' (Ahvenainen, 2003). The development of a whole range of active packaging systems, some of which may have applications in both novel and existing food products, is fairly new (Day, 2003). Active packaging includes additives or 'freshness enhancers' that can participate in a host of packaging applications and by so doing, enhance the preservation function of the primary packaging system (Table 3).

Intelligent packaging is packaging that in some way senses some properties of the food it encloses or the environment in which it is kept and which is able to inform the manufacturer, retailer and consumer of the state of these properties. Although distinctly different from the concept of active packaging, features of intelligent packaging can be used to check the effectiveness and integrity of active packaging systems (Hutton, 2003). Intelligent packaging has been defined as packaging 'systems which monitor the condition of packaged foods to provide information about the quality of the packaged food during transport and storage' (Ahvenainen, 2003). Smart packaging devices, which may be an integral component or inherent property of a foodstuff's packaging, can be used to monitor a plethora of food pack attributes (Table 3).

Table 3. Examples of active, intelligent and advanced consumer-pack interactive packaging systems for use with muscle based foods

PACKAGING SYSTEM	FUNCTION	
Active	Absorbing/Scavenging Properties	*Examples*: oxygen, carbon dioxide, moisture, ethylene, flavours, taints, UV light
	Releasing/Emitting Properties	*Examples*: ethanol, carbon dioxide, antioxidants, preservatives, sulphur dioxide, flavours, pesticides

	Removing Properties	*Examples*: catalysing food component removal (i.e. lactose, cholesterol)
	Temperature Control	*Examples*: insulating materials, self-heating and –cooling packaging, microwave susceptors and modifiers, temperature-sensitive packaging
	Microbial and Quality Control	*Examples*: UV and surface-treated packaging materials
Intelligent	Tamper Evidence and Pack Integrity	*Examples*: breach of pack containment
	Indicators of Product Safety/Quality	*Examples*: time-temperature indicators, gas sensing devices, microbial growth, pathogen detection
	Traceability/Antitheft Devices	*Examples*: Radio frequency identification (RFID), labels, tags, chips
	Product Authenticity	*Examples*: holographic images, logos, hidden design print elements, RFID
Advanced Consumer-Pack Interactive	Rapid Communication Technologies	*Examples*: pack provision of information following consumer access using smart-phones, etc.

	Smart Cooking Technologies and Oven Technology to Cook Meal	*Examples*: consumer engages with packaging

Kerry (2014) proposed a third category of technologies which he termed advanced consumer-pack interactive systems or consumer interactive systems (Table 3). Kerry (2014) proposed this smart packaging grouping as being different from active or intelligent packaging systems as these secondary devices (often printed electronics) can only function when consumers decide to interact with them (e.g. three-dimensional bar codes, RC labels or tags etc.: see Figure 1). The emergence of this unique grouping of technologies reinforces the point that the term smart packaging technologies should be capable to encompass many diverse technologies that collectively constitute examples of second level packaging.

Figure 1. 3D Smart Codes on Marks and Spencers muscle-based ready-meals for enhanced cooking using Smart Ovens

The development of smart packaging technologies has evolved significantly over the past 30 years and yet, the application of these to muscle-based food products in the market-place can still be classified as being in its infancy. This is most likely due to two primary

reasons; 1) the over-cautionary and restrictive attitudes demonstrated by regulatory bodies towards these technologies, therefore stifling research and development of technological development and application within this packaging area; and 2) failure of technical developers of smart packaging technologies to engage meaningfully with the retailing sector and *visa versa*, and to a lesser degree with product manufacturers. However, research developments within the area of smart packaging are progressing rapidly and potential applications are likely, despite the obstacles outlined.

4.3 Oxygen Scavengers

High levels of O_2 present in food packages may facilitate microbial growth, off-flavour and -odour development, colour changes and nutritional losses thereby causing significant reduction in the shelf life of foods. Therefore control of O_2 levels in food packages is important, to limit the rate of such deteriorative and spoilage reactions in foods. Oxygen absorbing systems provide an alternative to vacuum and gas flushing technologies as a means of improving product quality and shelf life (Ozdemir & Floros, 2004). Although O_2-sensitive foods can be packaged accordingly using MAP or vacuum packaging, such techniques do not always facilitate complete removal of O_2. O_2 which permeates through the packaging film or is trapped within the muscle tissue, within the product or trapped between product pieces or slices cannot be removed by these techniques. By using an O_2 scavenger, which absorbs the residual O_2 after packaging, quality changes in O_2-sensitive foods can often be minimised (Vermeiren, Devlieghere, Van Beest, De Kruijf, & Debevere, 1999). Existing O_2 scavenging technologies utilise one or more of the following concepts: iron powder oxidation, ascorbic acid oxidation, photosensitive dye oxidation, enzymatic oxidation (e.g. glucose oxidase and alcohol oxidase), unsaturated fatty acids (e.g. oleic or linolenic acid) rice extract or immobilised yeast on a solid substrate (Floros, Dock, & Han, 1997). More comprehensive information and details relating to O_2 scavengers can be obtained from other reviews (Floros, et al., 1997; Vermeiren, et al., 1999). Structurally, the O_2 scavenging component of a package can take the form of a sachet, label, film (incorporation of scavenging agent into the packaging film), card, closure liner or concentrate (Suppakul, Miltz, Sonneveld, & Bigger, 2003) – for example, see Figure 2.
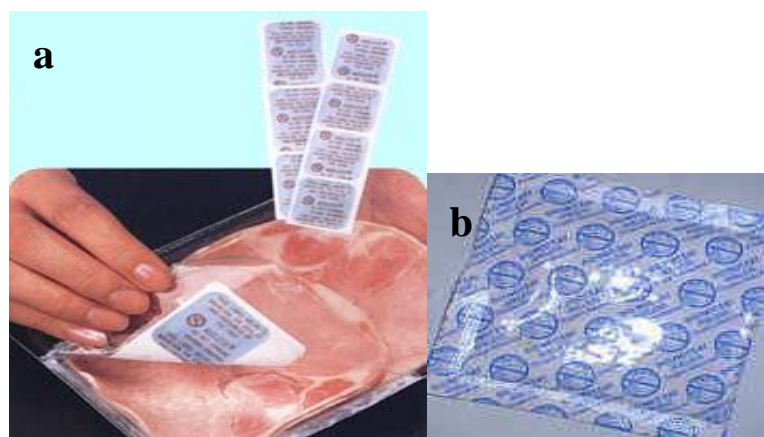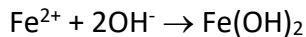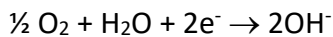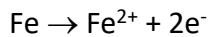

Figure 2. Ageless® O2 scavenging label (a) and sachet insert (b).

The majority of currently commercially available O_2 scavengers are based on the principle of iron oxidation, as per Equation 1 (Smith, Ramaswamy, & Simpson, 1990).

$$Fe \rightarrow Fe^{2+} + 2e^-$$

$$\frac{1}{2} O_2 + H_2O + 2e^- \rightarrow 2OH^-$$

$$Fe^{2+} + 2OH^- \rightarrow Fe(OH)_2$$

$$Fe(OH)_2 + \frac{1}{4} O_2 + \frac{1}{2} H_2O \rightarrow Fe(OH)_3 \qquad \text{Equation (1)}$$

Comprehensive details about a variety of commercially available O_2 scavengers are presented by Suppakul, et al. (2003). Ageless® (Mitsubishi Gas Chemical Co., Japan) is the most common O_2 scavenging system based on iron oxidation. These sachets are designed to reduce O_2 levels to less than 1%. Additional examples of O_2 absorbing sachets include ATCO® (Emco Packaging Systems, UK; Standa Industries, France), FreshPax® (Multisorb Technologies Inc., USA) and Oxysorb® (Pillsbury Co., USA), Oxy-Guard™ (Clariant) and OxyCatch® (Kyodo Printing Co., Japan).

The scientific literature contains a number of references to studies which examine the influence of O_2 scavenger sachets on fresh beef discoloration. This is based upon the intrinsic relationship between O_2 and myoglobin biochemistry in red meat, which, in turn, contributes to either an acceptable cherry-red colour as oxymyoglobin (OMb) accumulates or unacceptable discolouration with increasing metmyoglobin (MMb) content as OMb oxidises (Mancini & Hunt, 2005). Gill and McGinnis (1995) performed an O_2 absorption kinetics study with a commercial O_2 scavenger (FreshPax™ 200R) and reported that discoloration could be prevented in ground beef if large numbers of scavengers were used in each pack to bring residual O_2 to < 10 ppm within 2 hours at a storage temperature of -1.5°C. The inclusion of O_2 scavengers (Ageless® SS200) in master packs flushed with 50% CO_2 : 50% N_2 significantly improved the colour stability of *M. longissimus* and *M. psoas major*, relative to controls (Allen, Doherty, Buckley, Kerry, O'Grady, & Monahan, 1996). Tewari, Jayas, Jeremiah and Holley (2001) examined the effect of two commercial O_2 scavengers, (Ageless® FX-100 and FreshPax® R-2000) in conjunction with CAP, on the discoloration of *M. psoas major* in master packs filled with nitrogen (N_2) and stored at 1 ± 0.5°C. Steaks packaged without O_2 scavengers had more discoloration and significantly higher proportions of metmyoglobin when compared to steaks packaged with O_2 scavengers. Prevention of metmyoglobin formation was influenced by the number, but not the type of O_2 scavenger employed (Tewari, Jayas, Jeremiah, & Holley, 2001).

(Payne, Durham, Scott, & Devine, 1998) examined the effect of vacuum controlled atmosphere packaging (CAP) with CO_2. The treatments were, packs flushed with CO_2, packs flushed with CO_2 and containing Ageless™ (Z50) O_2 scavengers and packs containing O_2 scavengers alone. The effect on drip loss, microbial and sensorial properties of *M. longissimus lumborum* stored for up to 20 weeks at -1.5°C was examined. Beef in

packs flushed with CO_2 and flushed containing the O_2 scavenger had lower drip loss than the standard CAP system. The packages flushed with CO_2 and those containing the O_2 scavenger alone gave the best results in regards to drip loss, microbial and sensory properties, depending on the storage shelf-life required.

In addition to fresh beef, O_2 scavenging technology has also been applied to pork (Doherty & Allen, 1998) and pork products, where, Martínez, Djenane, Cilla, Beltrán, and Roncalés (2006) reported that fresh pork sausages stored in 20% CO_2 : 80% N_2 plus an O_2 scavenger (Ageless® FX-40) for up to 20 days at $2 \pm 1°C$ had reduced psychrotrophic aerobe counts and an extended shelf-life in terms of colour and lipid stability. Smith, Hoshino, and Abe (1995) described the successful usage of Ageless® O_2 scavengers in minimising chemical and microbial spoilage of seafood products at the retail level, which included; dried seaweed, dried salmon jerky, dried sardines, dried shark's fin, dried rose mackerel, dried cod, dried squid, fresh yellow tail, sliced salmon, dried/smoked salmon, dried octopus leg, dried bonito, salmon roe, dried squid/vinegar/soybean sauce and sea urchin. It could be argued that because of the unique composition that certain seafood products possess (i.e. unique pigmentation, high levels of polyunsaturated fats and high initial microbiological loadings) that such products are the most apt in terms of utilising O_2 scavenging technologies within first level packaging systems to minimise the effects of O_2 on these components.

Oxygen scavenging labels are widely used commercially as O_2 scavengers in pre-packed cooked meat products. Emco Packaging Systems, specialists in active and intelligent packaging, are a UK manufacturer and distributor for ATCO® DE 10S self adhesive O_2 absorbing labels. Emco supply ATCO® labels for use in pre-packed sliced cooked meats, especially hams, to meat processors in Ireland, throughout the UK and in Europe. While labels used in sliced cooked meat packages scavenge between 10 and 20 cc's of O_2, Emco have recently launched larger O_2 scavenging labels onto the market (ATCO® 100 OS and 200 OS), which scavenge between 100 and 200 cc's O_2, for use in larger capacity packaging applications.

An alternative to sachets involves the incorporation of the O_2 scavenger into the packaging structure itself. This minimizes negative consumer responses and offers a potential economic advantage through increased outputs. It also eliminates the risk of accidental rupture of the sachets and inadvertent consumption of their contents (Suppakul et al., 2003).

Cryovac® 0S2000™ polymer-based O_2 scavenging film was developed by Cryovac Div., Sealed Air Corporation, USA (See Figure 3). This UV light-activated O_2 scavenging film, which structurally is composed of an O_2 scavenger layer extruded into a multilayer film, can reduce headspace O_2 levels from 1% to ppm levels in $4 - 10$ days and is therefore comparable with O_2 scavenging sachets. The OS2000™ scavenging films have applications in a wide variety of food products including dried or smoked meat products and processed meats (Butler, 2002). A similar UV light-activated O_2 scavenging polymer ZERO2™, was developed by Commonwealth Scientific and Industrial Research Organisation (CSIRO), Division of Food Science Australia in collaboration with VisyPak

Food Packaging, Visy Industries, Australia, and it forms a layer in a multi-layer package structure and has similar applications, including reduced discoloration of sliced meats. Since the film developments described above, different approaches have been used in conjunction with film application for the control of O_2 levels in food packs. Bioka Ltd. (Finland) manufactures an enzyme-based O_2 scavenger which consists of two enzymes, namely; glucose oxidase/catalase.
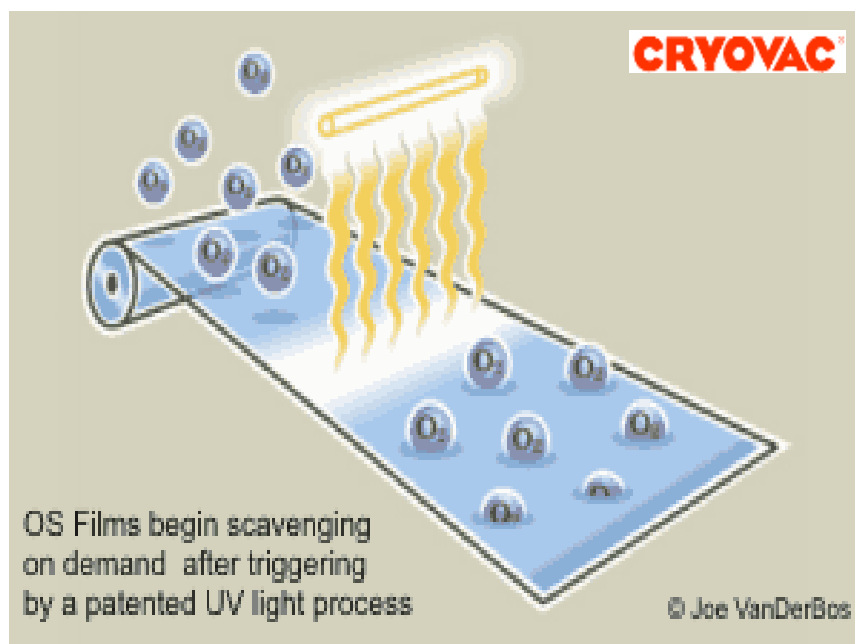
Figure 3. An example of an O2 scavenging film from Cryovac®.

Some rather interesting packaging materials that have emerged in recent times and which possess O_2 scavenging properties are rigid laminated plastic-based containers, which have been used to date for muscle-based food products such as; soups, stews and convenience-style, ready meals. These high O_2 barrier and high temperature tolerant (PP/EVOH/PP) tubs and containers have been launched onto the market by RPC Bebo Plastik GmbH (Germany). The O_2 scavenging activity within the containers is supplied through the addition of Shelfplus® (Albis Plastik GmbH, Germany) into the extruded PP component of the laminate. Similarly, other high temperature O_2 scavenging systems are already available for application in retort or pressure cooking applications. Mullinix Packages Inc. (USA) has developed Oxy*RX*™ O_2 scavenging rigid PET-based containers which can be offered in numerous formats for a multitude of applications. The company claims that that the O_2 scavenging activity of the Oxy*RX*™ materials has been shown to be effective in preventing any O_2 being detected in the headspace of packaged and processed products four years after initial processing (Mullinix web page: www.mullinixpackages.com). Mitsubishi Gas Chemical Inc. (Japan) has also developed OMAC® film technology, which is O_2 scavenging in nature, and can also be used for high temperature and retorting applications.

One rather novel O_2 scavenger system was documented by Altieri, Sinigaglia, Corbo, Buonocore, Falcone, and Del Nobile (2004). These researchers manufactured O_2-scavenger films using aerobic microorganisms as the "active compound". They entrapped the microorganisms *K. varians* DSM 20033 and *P. subpelliculosa* in a polymeric film of either hydroxyethyl cellulose (HEC) or PVA. These researchers found that the desiccated film could be stored over a period of 20 days without any appreciable decrease in microbial viability. These films were able to remove O_2 from the vial-active space however, these authors suggested that the best efficiency of O_2 absorption might be achieved by using the film as an active coating for high humidity foods.

4.4 Carbon Dioxide Emitters and Scavengers

The function of CO_2 with a packaging environment is to suppress aerobic microbial growth. Therefore a CO_2 generating system can be viewed as a technique complimentary to O_2 scavenging (Suppakul, et al., 2003). Since the permeability of CO_2 is 3 to 5 times higher than that of O_2 in most plastic films, it must be continuously produced to maintain the desired concentration within the package (Ozdemir & Floros, 2004). High CO_2 levels (10-80%) are desirable for muscle-based foods such as meat, poultry and seafood, in order to inhibit surface microbial growth and extend shelf life. Removal of O_2 from the package creates a partial vacuum which may result in the collapse of flexible packaging. Additionally, when a package is flushed with a mixture of gases including CO_2, the CO_2 dissolves in the product creating a partial vacuum. In these aforementioned situations, the simultaneous release of CO_2 from inserted sachets which consume O_2 is desirable. Such systems are based on either ferrous carbonate or a mixture of ascorbic acid and sodium bicarbonate (Rooney, 1995). Examples of commercially available dual action combined CO_2 generators/O_2 scavengers are Ageless® G (Mitsubishi Gas Chemical Co, Japan) and FreshPax® M (Multisorb Technologies Inc, USA). Sivertsvik (1999) showed that by combining various approaches to MAP with O_2 absorbing and CO_2 releasing forms of active packaging the microbiological quality of salmon fillets were superior to other packaging approaches investigated which omitted the use of intelligent packaging devices.

Carbon dioxide emitting sachets or labels can also be used independently. The Verifrais™ package, manufactured by SARL Codimer (Paris, France) has been used to extend the shelf life of fresh meats and fish. This innovative package consists of a standard MAP tray, but has a perforated false bottom under which, a porous sachet containing sodium bicarbonate/ascorbate is positioned. When juice exudates from the packaged meat drips onto the sachet, CO_2 is emitted, thus replacing any CO_2 absorbed by the meat and preventing package collapse. The product CO_2 Fresh Pads patented by CO_2 Technologies functions in a similar manner and has been positioned in the market to be used for meat, poultry and seafood products. Like moisture absorbing pads (which will be described later), the drip or moisture loss from these muscle foods is absorbed into the pads where upon the moisture reacts with citric acid and sodium bicarbonate contained within the pads, consequently resulting in the generation of CO_2 which contributes to the internal atmosphere of the package, thereby enhancing product preservation. Similarly, the

UltraZap® XtendaPak (Paper Pak Industries, North America) active pad includes additives that produce CO_2 as moisture from muscle-based products makes contact with these additives as it passes through the cellulosic materials of these active pads.

The SUPERFRESH packaging technology developed by Vartdal Plastindustri AS (Norway) is comprised of a rigid expanded polystyrene box containing a CO_2 emitter. The boxes are designed to hold fresh fish for transportation and extend shelf-life. The CO_2 emitters can be designed to cope with varying challenges presented by different fish species (i.e. physical dimensions). The emitter is placed in the bottom of each box; the fish placed on top and the box is packaged with a protective atmosphere and sealed. Over time, moisture emanating from the fish makes contact with the emitter, thereby setting up a chemical reaction which results in the contained generation of CO_2. This results in an extension of the shelf-life of the packaged seafood products.

The inhibition of spoilage bacteria utilising active packaging technology may reduce bacterial competition and thus permit growth and toxin production by non-proteolytic *C. botulinum* or the growth of other pathogenic bacteria (Sivertsvik, 2003). Lövenklev, Artin, Hagberg, Borch, Holst, and Rådström (2004) reported that while a high concentration of CO_2 decreased the growth rate of non-proteolytic *C. botulinum* type B, the expression and production of toxin was greatly increased. This may increase the risk of botulism instead of its reduction as per the use of MAP systems. Research into the safety risks associated with the use of CO_2 in packaging systems is necessary.

CO_2 absorbers (sachets) may consist of either calcium hydroxide and sodium hydroxide, or potassium hydroxide, calcium oxide and silica gel. These can be used to remove CO_2 during storage in order to prevent gas generated pressure build up and bursting of the package. Possible applications include their use in packs of dehydrated poultry products and beef jerky (Ahvenainen, 2003) as well as in fermented or roasted foods (Lee, Shin, Lee, Kim, & Cheigh, 2001). CO_2 scavengers can be composed either of a physical absorbent such as Zeolite or an active carbon powder; or of a chemical absorbent such as calcium hydroxide, sodium carbonate, magnesium hydroxide etc. (Charles, Sanchez, & Gontard, 2006). One such example is the use of CO_2 absorbers in the form of Zeolite and active carbon to control the pressure build up and volume expansion of *kimchi* (fermented foods often containing meat and fish) packages due to CO_2 production during fermentation (Lee et al., 2001).

4.5 Moisture Control

The main purpose of liquid water control is to lower the water activity (a_w) of the product, thereby suppressing microbial growth (Vermeiren, et al., 1999). Temperature cycling of high a_w foods has led to the use of plastics with an anti-fog additive that lowers the interfacial tension between the condensate and the film. This contributes to the transparency of the film and enables the customer to clearly see the packaged food (Rooney, 1995) although it does not affect the amount of liquid water present inside the package. Several companies manufacture drip absorbent sheets or pads such as Cryovac Dri-Loc® (Sealed Air Corporation, USA), Thermarite® or Peaksorb® (Australia), Toppan™

(Japan), MoistCatch (Kyodo Printing Co. Ltd., Japan), MeatGuard, VacuumGuard and FishGuard (McAirlaid Inc., USA and Europe) and moisture absorbent trays such as Fresh-R-Pax™ (Maxwell Chase Technologies, LLC, USA) and Linpac trays (Linpac Packaging Ltd., UK) for liquid control in high a_w foods such as meat, poultry and seafood. These systems generally consist of a super absorbent polymer located between two or more layers of a microporous or non-woven polymer or cellulosic material. This material can be supplied as sheets of various sizes and is used as drip-absorbing pads which can typically be found in tray formatted (overwrap and MAP) fresh muscle food products, including; beef steaks, premium beef roasts, pork loin chops, lamb chops, lamb leg cuts, poultry pieces, fresh chickens, turkeys and ducks, fish cutlets, fish darnes and skinless fish fillets (See Figure 4). The format and dimension of the pad for application is determined by the size and weight of the product to be placed in the tray and on the anticipated drip loss emanating from specific product types.

Figure 4. An example of drip-absorbing pads (indicated by arrow) used as a moisture control in muscle-based food packaging

A novel approach to extending the shelf-life of fresh fish is presented in the commercial form called 'Pitchit Films' which have been developed by The Showa Denko Company in Tokyo, Japan. Pitchit films form a kind of pillow pack which contains propylene glycol held between layers of polyvinyl alcohol (PVA). PVA is traditionally used in laminate constructions because of its excellent gas barrier properties, however, this capacity is only be achieved when the PVA layer is sandwiched between two packaging layers that protect it from water which otherwise limits its performance. While PVA is permeable to

water, it is impermeable to propylene glycol. Consequently, when this film is wrapped around muscle foods, the propylene glycol absorbs free water from the product surface through the PVA film, thereby preventing spoilage microorganisms from proliferating and extending product shelf-life. The use of such films reduced microbial counts in seafood products (Labuza & Breene, 1989) and enhanced colour characteristics in a range of muscle foods (Arakawa, Chu, Otsuka, Kotoku, & Takuno, 1990).

TenderPac (SEALPACK, Europe) is an interesting dual-compartment vacuum packaging system, which creates optimal conditions for meat products which are intended to be aged or matured; and the retail formatting allows for this to take place while the packaged meat product sits on retail shelving. Whether produced from cost-efficient PA/PE flexible film or applied as high-quality TraySkin® solution, TenderPac is perfectly tuned to the maturation process of fresh red meat. A second compartment, separated by a porous seam and covered by a pre-printed film or label, neatly collects the meat's drip-loss by means of the special ActiveStick. This ensures that the meat is stored dry and appetizingly during its entire shelf-life (SEALPACK web page: www.sealpack.com).

Another innovative and alternative moisture absorbing technology comes in the form of flexible microwave packaging called Nor®Absorbit (Nordenia International Ag, Germany). This film allows greasy or breaded muscle-based foods to be prepared in the microwave so that they are crisp and tasty. The innovative and flexible Nor®Absorbit microwave packaging absorbs both moisture and grease during cooking in the microwave. The food is thus cooked directly in the sales packaging until it is crispy. Preparation is noticeably more convenient, shorter and cleaner than conventional pan frying (NORDENIA International web page: www.mondigroup.com).

4.6 Antimicrobial Packaging

Food spoilage is any change which renders a food product unfit for human consumption (Hayes, 1992). Food spoilage is an important global issue with some figures suggesting that 25% of all the world's food supply is lost through microbial spoilage alone (Huis in't Veld, 1996). In developed countries the majority of spoilage can be attributed to microbial activity, usually by psychrotrophic microorganisms, yeasts and moulds. This may present itself as visible growth (slime, colonies), as textural changes (degradation of polymers) or as off-odours and -flavours (Gram, Ravn, Rasch, Bruhn, Christensen, & Givskov, 2002). The type of organism involved in spoilage of a food or beverage product depends greatly on the characteristics of the product as a substrate base and on processing, preservation and storage conditions. The degree of proliferation of the spoilage organisms present depends on a number of physical properties of the muscle-based food product. These include intrinsic parameters such as a_w, pH and redox potential; and extrinsic environmental factors such as storage temperature, humidity and the surrounding atmosphere. Microbial spoilage is most rapid in proteinaceous foods such as meat, poultry, fish, milk and some other dairy products, as these products are highly nutritious, possess a neutral or slightly acid pH and have a high a_w (Huis in't Veld, 1996).

Microbial contamination and subsequent growth reduces the shelf life of foods and increases the risk of food borne illness. Traditional methods of preserving foods from the effect of microbial growth include thermal processing, drying, freezing, refrigeration, irradiation, MAP and addition of antimicrobial agents or salts. However, many of these techniques cannot be applied to all food products (i.e. fresh meats) (Quintavalla & Vicini, 2002). Antimicrobial packaging is a promising form of active packaging especially for meat products. Since microbial contamination of meat products occurs primarily upon the surface, due to post processing handling, attempts have been made to improve safety and to delay spoilage by the use of antibacterial sprays or dips. These approaches are limited as a result of neutralisation of antibacterial compounds on contact with the meat surface or their diffusion from the surface into the meat mass. Incorporation of bactericidal agents into meat formulations may result in partial inactivation of the active compounds by meat constituents and therefore exert a limited effect on surface microflora (Quintavalla & Vicini, 2002). Antimicrobial food packaging materials have to extend the lag phase and reduce the growth phase of microorganisms in order to extend shelf life and to maintain product quality and safety (Han, 2000). Comprehensive reviews on antimicrobial food packaging have been published by Appendini and Hotchkiss (2002) and Suppakul et al. (2003). To confer antimicrobial activity, antimicrobial agents may be coated, incorporated, immobilised, or surface modified onto package materials (Suppakul et al., 2003), albeit pending national or international food safety committee approval. A comprehensive list of antimicrobial agents for use in antimicrobial films, containers and utensils is presented in a review by Suppakul et al. (2003). The classes of antimicrobials listed range from acid anhydride, alcohol, bacteriocins, chelators, enzymes, organic acids and polysaccharides. Many antimicrobial members derived from these ingredient classes have been evaluated for their antimicrobial properties in various film structures, synthetic polymers and edible films.

Bacteriocins are bacterial proteinaceous products which are produced by a variety of bacteria to inhibit the growth of closely related species (Farkas-Himsley, 1980). A number of these have been incorporated into packaging systems with a view to inhibiting microbial growth. In one study Enterocin 416K1, a bacteriocin produced by *E. casseliflavus* IM 416K1 was entrapped in an organic–inorganic hybrid coating applied to a LDPE (low-density polyethylene) film (Iseppi, Pilati, Marini, Toselli, de Niederhäusern, Guerrieri, Messi, Sabia, Manicardi, & Anacarso, 2008) and was evaluated for anti-listerial properties. Coating was achieved by spin-coating followed by thermal deposition using a poly(ethylene)-block-poly(ethylene glycol) (PE-PEG) co-polymer. The study demonstrated that the activated coatings significantly inhibited the growth of *L. monocytogenes* in artificially contaminated food samples (frankfurters and fresh cheeses) at both room and refrigeration temperatures. Nisin is another bacteriocin which has also been shown to exhibit antimicrobial properties (Cao-Hoang, Grégoire, Chaine, & Waché, 2010; Nguyen, Gidley, & Dykes, 2008). Cao-Hoang et al. (2010) produced nisin-containing sodium caseinate films, produced by a standard casting protocol (Kristo, Koutsoumanis, & Biliaderis, 2008), which showed an ability to inhibit the growth of *L. innocua* in inoculated soft cheese by direct surface contact.

Lysozyme is one of the most frequently used biopreservatives in antimicrobial packaging (Quintavalla & Vicini, 2002). This is an enzyme which shows antimicrobial activity mainly on Gram-positive bacteria by splitting the bonds between *N*-acetylmuramic acid and *N*-acetylglucosamine of the peptidoglycan in their cell walls (Mecitoğlu, Yemenicioğlu, Arslanoğlu, Elmacı, Korel, & Çetin, 2006). Lysozyme has been well studied as an active packaging constituent (De Souza, Fernández, López-Carballo, Gavara, & Hernández-Muñoz, 2010). Mecitoğlu et al. (2006) incorporated lyophilised lysozyme into an edible corn zein film and demonstrated that these films had an inhibitory effect on different bacteria including *B. subtilis* and *L. plantarum.* Lysozyme has also been combined with other antimicrobial agents in packaging systems. For instance, a mixture of lysozyme and nisin at a ratio of 3:1 (w/w) was applied to pork loins that were then stored in vacuum packages at 2 °C for up to 6 weeks. This mixture was shown to be effective in controlling the growth of lactic acid bacteria, which are otherwise able to grow in the presence of acetate and *B. thermosphacta* (Nattress & Baker, 2003). In another study, a lysozyme and nisin were again combined and applied to the surface of ready-to-eat turkey bologna, which was then pasteurised, vacuum packaged and refrigerated. The antimicrobial combination significantly reduced the recovery and growth of *L. monocytogenes* post-pasteurisation (Mangalassary, Han, Rieck, Acton, & Dawson, 2008). Other enzymes with potential antimicrobial activity (i.e. glucose oxidase) have been studied (Field, Pivarnik, Barnett, & Rand, 1986; Labuza & Breene, 1989; Padgett, Han, & Dawson, 1998), but less extensively.

The organic acids sorbic acid, p-aminobenzoic acid, lactic acid, and acetic acid, have long been recognised as generally recognised-as-safe (GRAS) food preservative options and there is a growing demand for natural preservatives such as these in the food industry (Burt, 2004). When used in combination with lactic and/or acetic acid, sorbic acid can inhibit the growth of *L. monocytogenes*, *S. typhimurium*, and *E. coli* O157:H7 in many low acid foods including; cold-pack cheese, bologna and beaker sausage (Cagri, Ustunol, & Ryser, 2001). Similarly, p-aminobenzoic acid has been reported to exhibit significant inhibitory activity against *L. monocytogenes*, *E. coli,* and *S. enteritidis* (Richards, Xing, & King, 1995). Edible whey protein isolate films incorporating sorbic acid and p-aminobenzoic acid have shown inhibitory action towards of *S. typhimurium*, *L. monocytogenes*, and *E. coli* O157:H7 when placed in direct contact with inoculated culture (Cagri et al., 2001). A study was also undertaken to evaluate antimicrobial films prepared by incorporating acetic or propionic acid into a chitosan matrix, with or without addition of lauric acid or the essential oil (EO), cinnamaldehyde (Ouattara et al., 2000). These films were directly applied to bologna, regular cooked ham or pastrami. Propionic acid was released from the chitosan matrix at a faster rate than acetic acid and the addition of lauric acid, but not cinnamaldehyde, to the chitosan matrix reduced the release of acetic acid. However, lactic acid bacteria were not affected by the antimicrobial films under study, but the growth of Enterobacteriaceae and *S. liquefaciens* was delayed or completely inhibited as a result of film application. Strongest inhibition was observed on drier surfaces (bologna), onto which acid release was slower, and with films containing cinnamaldehyde, as a result of its greater antimicrobial activity under these conditions. One novel study combined MAP packaging and organic acid incorporation on the

preservation of fresh salmon (Schirmer, Heiberg, Eie, Møretrø, Maugesten, Carlehøg, & Langsrud, 2009). Salmon was packed with a small amount of 100% CO_2 (gas/product ratio 0.2/1.0 v/v) and a brine solution containing various combinations of citric acid (3% w/w, pH 5), acetic acid (1% w/w, pH 5) and cinnamaldehyde (200 µg ml^{-1}). CO_2, acetic acid and citric acid alone each inhibited the growth of total bacterial counts, lactic acid bacteria, sulphur reducing bacteria and Enterobacteriaceae, but effects were enhanced in combination. It was found that the combination of CO_2 and organic acids completely inhibited bacterial growth during 14 days of storage at 4°C both in inoculation experiments and in experiments on salmon with natural background flora. The addition of cinnamaldehyde did not influence bacterial growth.

Many *in vitro* studies have demonstrated antibacterial activity of EO against *L. monocytogenes*, *S. typhimurium*, *E. coli* O157:H7, *S. dysenteria*, *B. cereus* and *S. aureus* at levels between 0.2 and 10 µl ml^{-1}. A number of EO components have been identified as effective antibacterials (i.e. carvacrol, thymol, eugenol, perillaldehyde, cinnamaldehyde and cinnamic acid) that have minimum inhibitory concentrations (MICs) of 0.05–5 µl ml^{-1} *in vitro*. A higher concentration is needed to achieve the same effect in foods (Burt, 2004). Direct application of eugenol, coriander, clove, oregano and thyme oils has been found to be effective at levels of 5–20 µl g^{-1} in inhibiting *L. monocytogenes*, *A. hydrophila* and autochthonous spoilage flora in meat products (Burt, 2004). EOs have also been used as antimicrobials in fish products, with a high fat content appearing to reduce effectiveness. For example, oregano oil at 0.5 µl g^{-1} was more effective against the spoilage organism *P. phosphoreum* on cod fillets than on salmon, which is a fatty fish (Mejlholm & Dalgaard, 2002). One study was conducted to evaluate the combined effect of low-dose gamma irradiation and EO coating on the shelf life of pre-cooked shrimp (Ouattara, Sabato, & Lacroix, 2001). Antimicrobial coatings were obtained by incorporating various concentrations of thyme oil and *trans*-cinnamaldehyde in coating formulations prepared from soy or whey protein isolates. Coated shrimps were stored at 4 ± 1°C under aerobic conditions. Results showed that gamma irradiation and coating treatments had synergistic effects in reducing the aerobic plate counts and *P. putida* numbers resulting in at least a 12 day extension of shelf life. However, an issue commonly associated with EOs was identified, namely that the incorporation of 1.8% EOs in the coating solutions significantly decreased the consumer sensory acceptability of the products.

Interest in biopolymers has increased greatly in recent years, owing to their renewable biodegradable nature and their natural derivation. Some polymers are inherently antimicrobial and have been used in films and coatings. Polylactic acid (PLA) is one such polymer and is made primarily from renewable agricultural (i.e. corn) sources (Cutter, 2006). PLA polymers are composed of chains of lactic acid and exhibit high tensile strength, are resistant to oil-based products, sealable at low temperatures and can act as flavour and odour barriers for foods (Cutter, 2006). Several studies have shown the antimicrobial effect of PLA. Mustapha, Ariyapitipun, and Clarke (2002) demonstrated the effect of PLA alone or in combination with lactic acid or nisin against *E. coli* O157:H7 in vacuum packaged, irradiated, raw meat. However, these authors noted here that the inhibitory action was not significantly greater than lactic acid alone. Other studies also identified the antimicrobial action PLA, but also showed limitations. Chellappa (1997)

examined the effect of PLA for reducing pathogens on raw meat. *E. coli* O157:H7, *L. monocytogenes*, *S. typhimurium*, or *Y. enterocolitica* associated with lean beef surfaces were treated with PLA, lactic acid, or sterile water. PLA treatments at pH of 3.0 resulted in significant reductions of *E. coli* O157:H7; however, *E. coli* O157:H7 was not inhibited when PLA was applied at pH 5.0, 6.0, and 7.0 (Chellappa, 1997). These limitations suggest PLA may be best utilised in active packaging systems through combination with other active molecules like nisin, as above, or by blending with other biopolymers with complimentary properties like chitosan (Suyatma, Copinet, Tighzert, & Coma, 2004).

Chitosan is a linear polysaccharide consisting of (1, 4)-linked 2-amino-deoxy-β-d-glucan, and is a deacetylated derivative of chitin, which is the second most abundant naturally found polysaccharide after cellulose. Chitosan has been found to be non-toxic, biodegradable, biofunctional, biocompatible in addition to having antimicrobial characteristics (Dutta, Tripathi, Mehrotra, & Dutta, 2009). Edible film coatings of chitosan alone or in combination with another biopolymer, sodium caseinate have been applied to salami samples (Moreira, Pereda, Marcovich, & Roura, 2011). Chitosan and sodium caseinate/chitosan films exerted a significant bactericidal action on mesophilic, psychrotrophic bacteria, as well as a reduction in yeast and mould counts. Greater bactericidal properties were observed in the caseinate/chitosan than in the chitosan alone. This can be attributed to the greater film-forming and thermoplastic properties of sodium caseinate (i.e. the polymers work synergistically). To harness its antimicrobial properties and overcome its weak film-forming properties chitosan has also been cross-linked with existing packaging polymers. One study developed an antimicrobial coating based on chitosan and PVA and evaluated its effect on minimally processed tomato (Tripathi, Mehrotra, & Dutta, 2009). Films were prepared by blending chitosan and PVA with glutaraldehyde as a cross-linker and fourier-transform infrared spectroscopy (FTIR) observed that a molecular miscibility between PVA and chitosan was achieved. The microbiological screening demonstrated the antimicrobial activity of the film against *E. coli, S. aureus,* and *B. subtilis*. Chitosan-based films have also been experimented with in the packaging of meat, fish and other food products (Darmadji & Izumimoto, 1994; Dutta, et al., 2009; Jongrittiporn, Kungsuwan, & Rakshit, 2001). A number of other biopolymers have been investigated in relation to antimicrobial packaging. Among these is the seaweed-derived alginate which possesses good film forming properties. This film has demonstrated an ability to reduce microbial counts, however it has often been found to compromise product sensory attributes owing to the bitterness imparted by the calcium chloride required to set them (Dang, Vermeulen, Ragaert, & Devlieghere, 2009).

Other sourced antimicrobials which have been incorporated directly into polymers are triclosan, fungi and silver zeolites (Quintavalla & Vicini, 2002), with the latter being the most widely used of these. Sodium ions present in zeolites are substituted by silver ions, which are antimicrobial against a wide range of bacteria and moulds. These substituted zeolites are incorporated into polymers like polyethylene, polypropylene, nylon and butadiene styrene at levels of 1–3% (Appendini & Hotchkiss, 2002).

Examples of commercial antimicrobial materials in the form of concentrates (e.g. AgION™, AgION Technologies LLC, USA) extracts (Nisaplin® (Nisin), Integrated Ingredients,

USA) and films (Microgard™ Rhone-Poulenc, USA) have been presented. Antimicrobial packages have had relatively few commercial successes outside of Japan where silver (Ag), or Ag-substituted zeolite, is the most common antimicrobial agent incorporated into plastics and commercial examples of these systems include; AgION®, Apacider®, Bactekiller, Bactiblock®, Biomaster®, d_2p®, IonPure®, IrgaGuard®, Novaron, Surfacine® and Zeomic®. Silver-ions inhibit a range of metabolic enzymes and have strong antimicrobial activity (Vermeiren et al., 1999). For example, the collaboration between Addmaster (UK) and Linpack Packaging Ltd. (UK) has led to the development of silver-coated films and trays targeted specifically to address microbial pathogens potentially contained in fresh muscle foods. Similarly, Food-touch® (Microbeguard Inc., USA) is an AgIon® silver coated paper which is intended to be used as interleafing materials between muscle-based products during transport. While it is anticipated that silver-based packaging will become more popular in time and will find commercial employment within packaging systems for muscle-based food products, currently legislators, retailers and muscle food processors remain cautious, despite their legislative inclusion in provisionally permitted food contact material listings within the EU and the USA.

4.6.1 Coating of Films with other non-Silver-based Antimicrobial Agents

Coating of films with antimicrobial agents can result in effective antimicrobial activity. Natrajan and Sheldon (2000) carried out a study to evaluate the potential use of packaging materials as delivery vehicles for carrying and transferring nisin-containing formulations onto the surfaces of fresh poultry products. The efficacy of nisin coated (100 μg/ml) polymeric films of varying hydrophobicities (polyvinyl chloride (PVC), linear low-density polyethylene (LLDPE) and nylon) in inhibiting S. *typhimurium* on fresh broiler drumstick skin was evaluated. It was concluded that packaging films coated with nisin were effective in reducing S. *typhimurium* on the surface of fresh broiler skin and drumsticks. Mitsuubishi-Kagaku Foods Corporation (Japan) developed Wasaouro™, a technology consisting of allyl isothiocyanate coatings for application to sheets, labels and films to control bacterial and mycological spoilage in both fresh and processed muscle-based food products.

4.6.2 Incorporation of Antimicrobial Agents

The direct incorporation of antimicrobial additives in packaging films is a convenient means by which antimicrobial activity can be achieved. Ouattara et al. (2000) carried out a study to assess the inhibition of surface spoilage bacteria in processed meats following the application of antimicrobial films prepared with chitosan. Antimicrobial films were prepared by incorporating acetic or propionic acid into a chitosan matrix, with or without addition of lauric acid or cinnamaldehyde, and were applied onto bologna, regular cooked ham or pastrami. During the storage period, packages were opened and the amounts of antimicrobial agents remaining in the chitosan matrix were measured. Propionic acid was released from the matrix must faster than acetic acid. Addition of lauric acid, but not cinnamaldehyde, to the chitosan matrix reduced the release of acetic acid and the release was more limited onto bologna than onto ham or pastrami. Lactic acid bacteria were

unaffected by the antimicrobial films studied whereas growth of *Enterobacteriaceae* and *S. liquefaciens* (surface-inoculated onto the meat products) was delayed or completely inhibited as a result of film application. The strongest inhibition was observed on drier surfaces (bologna), onto which, lauric acid release was slower, and with films containing cinnamaldehyde, as a result of its greater antimicrobial activity under these conditions. Vermeiren, Devlieghere, and Debevere (2002) reported that a 1.0% triclosan film had a strong antimicrobial effect *in vitro* simulated vacuum packaged conditions against the psychrotrophic food pathogen *L. monocytogenes*. However the triclosan film did not effectively reduce spoilage bacteria and growth of *L. monocytogenes* on refrigerated vacuum packaged chicken breasts stored at 7°C.

Ha, Kim, and Lee (2001) examined the effect of grapefruit seed extract (GFSE), a natural antimicrobial agent, incorporated (0.5% or 1% concentration) by co-extrusion or a solution-coating process in multilayered polyethylene (PE) films, on the microbial status and quality (CIE colour values [L*, a*, b*], 2-thiobarbituric acid reactive substances (TBARS) and pH) of fresh minced beef. The antimicrobial activity of the fabricated multilayer films was also evaluated using an agar plate diffusion method. It was reported that coating the PE film with GFSE with the aid of a polyamide binder resulted in greater antimicrobial activity compared to GFSE incorporation by co-extrusion. Using an agar diffusion test, the co-extruded film with 1% w/w GFSE showed antimicrobial activity against *M. flavus* only, whereas a film coated with 1% GFSE showed activity against several microorganisms such as *E. coli*, *S. aureus* and *B. subtilis*. Both types of GFSE-incorporated multilayer PE films reduced the growth of aerobic and coliform bacteria in minced beef wrapped with film and stored for up to 18 days at 3°C, relative to controls. The film coated with a higher concentration (1%) of GFSE had a more pronounced effect in inhibiting bacterial growth compared to the other films tested. GFSE-coated films were better than co-extruded films in preserving the chemical quality (TBARS) of packaged beef. Beef colour was unaffected by packaging treatment. The level of GFSE employed (0.5% and 1%) did not differ significantly in terms of film efficacy for preservation of beef quality.

There is a growing interest in edible coatings due to factors such as environmental and health concerns, the need for new storage techniques, and opportunities for creating new markets for under utilised agricultural commodities with film forming properties (Quintavalla & Vicini, 2002). Edible coatings and films prepared from polysaccharides, proteins and lipids have a variety of advantages such as biodegradability, edibility, biocompatibility, aesthetic appearance and barrier properties against O_2 and physical stress. The advantages of using edible coatings and films on meat and meat products have been discussed by Gennadios, Hanna, and Kurth (1997). Edible coatings could:

- Help alleviate the problem of moisture loss during storage of fresh or frozen meats.

- Hold juices of fresh meat and poultry cuts when packed in retail plastic trays.

- Reduce the rate of rancidity caused by lipid oxidation and myoglobin oxidation.

- Reduce the load of spoilage and pathogenic microorganisms on the surface of coated meats.

- Restrict volatile flavour loss and foreign odour adoption.

As an application of active packaging, edible coatings carrying antioxidants or antimicrobials can be used for the direct treatment of meat surfaces. In the case of edible films and coatings, selection of the incorporated active ingredient is limited to edible compounds therefore edibility and safety is important. Siragusa and Dickson (1993) demonstrated that alginate coatings containing organic acids were marginally effective on beef carcasses, reducing levels of *L. monocytogenes, S. typhimurium* and *E. coli* 0157:H7 by 1.80, 2.11 and 0.74 log cycles, respectively. Complete inhibition of *L. monocytogenes* on ham, turkey breast and beef was achieved using pediocin or nisin fixed on a cellulose casing (Ming, Weber, Ayres, & Sandine, 1997). Commercial application of this technology is described in a Wilhoit (1996) patent assigned to a manufacturer of cellulose food casings (Viskase Co Inc., USA). The package is a film, such as a polymer film or a regenerated cellulose film, containing heat resistant *Pediococcus*-derived bacteriocins in synergistic combination with a chelating agent to inhibit or kill *L. monocytogenes* on contact with food (Katz, 1999).

4.6.3 Immobilisation

Some antimicrobial packaging systems utilise covalently immobilised antimicrobial substances which suppress microbial growth. Scannell, Hill, Ross, Marx, Hartmeier, & Arendt (2000) investigated the immobilisation of bacteriocins, nisin and lacticin 3147 to packaging materials. The plastic film (PE/polyamide (70:30) formed a stable bond with nisin, in contrast to lacticin 3147, and maintained activity for a 3 month period both at room temperature and under refrigerated storage conditions. The antimicrobial packaging reduced the population of lactic acid bacteria in ham stored in MAP (60% N_2: 40% CO_2), thereby extending product shelf life. Nisin-adsorbed bioactive inserts reduced the level of *L. innocua* and *S. aureus* in hams.

4.6.4 Other Naturally-derived Antimicrobial Agents used in Smart Packaging Applications

The use of naturally-derived antimicrobial agents is important as they represent a lower perceived risk to the consumer (Nicholson, 1998). Skandamis and Nychas (2002) studied the combined effect of volatiles of oregano EO and modified atmosphere conditions (40% CO_2: 30% O_2: 30% N_2, 100% CO_2, 80% CO_2, vacuum packaged and aerobic storage) on the sensory, microbiological and physiochemical attributes of fresh beef stored at 5 and 15°C. Filter paper containing absorbed EO was placed in the packages, but not in direct contact with the beef samples. The shelf life of beef samples followed the order: aerobic storage < vacuum packaged < 40% CO_2: 30% O_2: 30% N_2 < 80% CO_2: 20% air < 100% CO_2. Longer shelf life was observed in samples supplemented with the volatile compounds of oregano EO.

Ethanol is another example of a naturally-derived antimicrobial agent. The incorporation of ethanol in films and sachets for slow release and ethanol vapour generation within food packs has led to the development of commercial products like; Ethicap, Antimold 102, Negamold (Freund Industrial), Oitech (Nippon Kayaku), ET Pack (Ueno Seiyaku) and Ageless type SE (Mitsubishi Gas Chemical) and many of these systems have been used in the packaging of semi-moist and dried fish products (Day, 2003).

4.7 Antioxidative Packaging

Oxidation is a major mechanism of food deterioration. Lipid oxidation is associated with the development of rancidity and loss in nutritive value of meat products (Maqsood & Benjakul, 2010). This is a particular problem in the packaging of fresh products containing high fat levels, particularly if the fat in question is polyunsaturated in natural form or composition, as found in many muscle-based food products.

While many studies have been reported on the benefits of applying antioxidants directly to muscle-based food products in terms of extending chemical shelf-life stability, little attention has focused on applying antioxidants to packaging materials as an alternative means of exerting the same controlling action on food products, but in a much more indirect and non-contributing manner.

While limited, antioxidants have been incorporated into active packing systems. Huang and Weng (1998) investigated the effects of wrapping fish fillets and fish oil in butylated hydroxytoluene (BHT) infused polyethylene-based films. These authors showed that lipid oxidation was reduced in both products by the presence of this synthetic antioxidant compared to non-packaged controls. Active films containing the natural antioxidant oregano extract were tested for their ability to extend the shelf life of beef steaks through the inhibition of lipid oxidation (Camo, Lorés, Djenane, Beltrán, & Roncalés, 2011). The active films were prepared according to an innovative procedure protected by the Gardes, & Roncales (2003) patent (Garces, Nerin, Beltran, & Roncalés, 2003) based upon covering a polypropylene film with a layer of varnish containing the oregano extract. The display life of beef samples with at least 1% oregano extract exhibited a significant increase in display life from 14 to 23 days and showed a reduction in TBARS indices. However, at oregano extract concentrations greater than 4%, the samples were unacceptable based on sensory-evaluation. In association with the research described above, ATOX® films coated with oregano oils have been developed by Artibal SA (Spain) for use in MAP fresh red meat packs to reduce lipid oxidation and discolouration in meat and bone. In another study, active packaging film containing antioxidants derived from barley husks achieved a reduction in lipid damage during frozen storage of Atlantic cod. The fish samples were packaged in low density polyethylene film coated with the barley husk extract. After six months, oxidation levels in the control sample were approximately 30–50% higher than in samples packaged in film containing antioxidants (Pereira de Abreu, et al. 2012b). This shows the potential of active forms of antioxidants in maintaining the sensory qualities and nutritional value of muscle-based food products.

4.8 Flavour/Odour Absorbers

During the storage of fresh and processed muscle-based food products, irregular production of off-odours and -flavours can be produced, a term which can be described as 'compartmentalised odour'. Such odours provide, in many cases, the false impression that the food product in question is putrid and inedible, leading to it being discarded by the consumer. Compartmentalised odour generation is complex and odours generated may be comprised of volatile components derived from the degradation of amino acids, fatty acids, aldehydes etc. from the muscle product, combining with packaging gases and other volatiles derived from the packaging materials. Packaged seafood products in particular, and poultry to a lesser degree, appear to suffer the most from this phenomenon - with hydrogen sulphide (H_2S) being present and associated with both poultry and seafood and trimethylamine (TMA) being present and associated with seafood.

Franzetti, Martinoli, Piergiovanni, & Galli (2001) investigated the effects of using an odour removing plastic packaging foam tray for various fish species; sole, hake and cuttlefish held under MAP conditions. The odour removing tray adsorbed TMA to a significant degree compared to the controls. Vermeiren, et al. 1999) described research conducted in Japan using polymers internally lined with acidic groups to strategically degrade the presence of amines (NH_3) on the surface of food products.

Flavour/odour adsorbers may have potential in active packaging technology for muscle-based food products. The Anico Co. (Japan) manufactured polymeric bags, called 'Anico' bags, that contained ferrous salt and an organic acid, which could be either citric or ascorbic acid, and were claimed to oxidise NH_3 and other oxidisable odour-causing compounds (Rooney, 1995). A number of companies have developed odour adsorbing technologies which are specific to this function or are combined with other active technologies; Multisorb Technologies (USA) commercially produced odour adsorbing sachets called MINIPAX1® and STRIPPAX1®, United Desiccants (USA) produced a packaging system that combined silica gel and activated carbon for both moisture absorption and odour adsorption in a product called 2-in-1, DuPont (USA) produced an odour and taste control (OTC) technology for aldehyde removal. While available and well described, few of these odour absorbers have been commercially trialled for use with muscle-based foods.

Adsorber systems employ mechanisms that exploit the properties of reagents, such as cellulose triacetate, acetylated paper, citric acid, ferrous salt/ascorbate and activated carbon/clays/zeolites. It has been reported that a Swedish company, EKA Noble in cooperation with a Dutch company Akzo, developed a range of synthetic aluminosilicate zeolites, which they claim absorb odorous gases within their highly porous structure (Rodney Abbott pers. comm.). Their BHM™ powder can be incorporated into packaging materials, especially those that are paper-based and apparently odorous aldehydes are adsorbed in the pore interstices of the powder (PIRA website: www.pira.co.uk). Similar

applications exist for various flavour emitting polymers (Ahvenainen, 2003), however, few of these are relevant or applicable to meat, fish or seafood.

4.9 Miscellaneous Potential Future Applications of other Smart/Active Technologies

In addition to smart packaging techniques described earlier, additional active technologies, applied to other foodstuffs (Ahvenainen, 2003) may have potential applications in muscle-based food products. For example, self-heating aluminium or steel cans and containers, currently used by coffee manufacturers (i.e. Nescafe, 'hot when you want it' beverages), may have application in the production of ready meals containing various muscle-based foods. Since consumer demand for ready-to-eat convenience meals is constantly increasing, packaging of ready-meals in self-heating active packaging is an important future application. Similarly, self-cooling technologies may hold some interest for usage with similar products in specific regions of the globe. Major technological developments, however, are still required.

Another releasing technology which has been developed recently by Curwood (FreshCase®) in the USA employs the use of sodium nitrite crystals in the sealing layer of laminated films (PET/EVOH or PVdC/EVA or LDPE) in order to assist in the fresh 'bloom' colour development of raw meat (Figure 5). The technology functions through the slow conversion of sodium nitrite to nitric oxide which interacts with myoglobin to provide a consumer-friendly fresh meat appearance. The levels of sodium nitrite can be easily manipulated so that higher (5-10 mg/g sealing material) levels of the agent can be applied for redder meats (beef) and lower (1 mg/g sealing material) levels for paler muscle-based foods (chicken) (Siegel & Nelson, 2012). This technology type holds a lot of promise in light of certain retailing chains opting to use vacuum-skin packaging formats for presentation of sub-primal meat cuts, such as steaks and loin chops. This type of technology offers retailers a solution to enhance fresh red meat appearance in anoxic vacuum pack formats.

Figure 5. An example of sodium nitrite crystals application to packaging films to promote red meat blooming: Freshcase ® (Curwood: USA)

Microwave susceptors consist of aluminium or stainless steel deposited on substrates such as polyester films or paperboard and serve to dry, crisp and ultimately brown microwave food. Modifiers for microwave heating consist of a series of antenna structures which alter the way microwaves arrive at food, thereby resulting in even heating, surface browning and crisping (Ahvenainen, 2003). Incorporation of such susceptors or modifiers into muscle-based product packages is an additional future application for active packaging of meat, poultry and fish-based products and technologies like Sira-Crisp® and SmartPouch® are leading the way in this regard.

4.10 Sensors

Many smart or intelligent packaging concepts involve the use of sensors and indicators. For the purposes of clarity these two areas will be discussed separately, although such a distinction is somewhat arbitrary and some overlap is unavoidable. The use of these systems is generally envisaged in terms of incorporation into established packaging techniques such as MAP and vacuum packaging.

MAP is an extremely important packaging technique used extensively for the distribution, storage and display of meat products in markets with a controlled cold distribution chain (Sivertsvik, Rosnes, & Bergslien, 2002). MAP works by replacing the air surrounding a meat product with formulated gas mixtures and thereby extending product shelf life and quality. The most important (non-inert) gases in MAP products are O_2 and CO_2 and their headspace partial pressures serve as useful indicators of the quality status of a meat product. The profiles of O_2 and CO_2 can change over time and are influenced by product type, respiration, packaging material, pack size, volume ratios, storage conditions, and package integrity, amongst others. A number of analytical techniques are available to monitor gas phases in the MAP products. Instrumental techniques such as gas

chromatograph (GC), both independent and in conjunction with mass spectroscopy (GC/MS) require compromise of package integrity and are time-consuming and expensive. Portable headspace O_2 and/or CO_2 gas analysers use 'minimally destructive' techniques (packages can be resealed) but tend not to be applicable to real-time, on-line control of packaging processes or large scale usage. An optical sensor approach offers a realistic alternative to such conventional methods (Peterson, Fitzgerald, & Buckhold, 1984).

A sensor is defined as a device used to detect, locate or quantify energy or matter, giving a signal for the detection or measurement of a physical or chemical property to which the device responds (Kress-Rogers, 1998b). To qualify as a sensor, a device must be able to provide continuous output of a signal. Most sensors contain two basic functional units: a receptor and a transducer. In the receptor, physical or chemical information is transformed into a form of energy which may be measured by the transducer. The transducer is a device capable of transforming the energy carrying the physical or chemical information about the sample into a useful analytical signal.

Research and development of sensor technology has, until recently, been largely concentrated in biomedical and environmental applications (Demas, DeGraff, & Coleman, 1999). The specifications of such sensors are, however, quite different from those required for food packaging applications. The development of improved methods to determine food quality such as freshness, microbial spoilage, oxidative rancidity or O_2 and/or heat induced deterioration is extremely important to food manufacturers. In order to maximise the quality and safety of foodstuffs, a prediction of shelf-life that is based on standard quality control procedures is normally undertaken. Replacement of such time-consuming and expensive quality measurements with rapid, reliable and inexpensive alternatives has lead to greater efforts being made to identify and measure chemical or physical indicators of food quality. The possibility of developing a sensor for rapid quantification of such an indicator is known as the marker approach (Kress-Rogers, 2001). Determination of indicator headspace gases provides a means by which the quality of a meat product and the integrity of the packaging in which it is held can be established rapidly and inexpensively. One means of doing so is through the production of intelligent packaging incorporating gas sensor technology.

Chemical sensor and biosensor technology has developed rapidly in recent years. The main types of transducers with potential use in meat packaging systems include; electrical, optical, thermal or chemical signal domains. Sensors can be applied as the determinant of a primary measurable variable or, using the marker concept, as the determinant of another physical, chemical or biological variable (Kress-Rogers, 1998a). In the case of headspace gas sensing, accurate measurements are desirable as indicators of meat, poultry and seafood product quality. Recent developments in sensor technology has narrowed the gap between the theoretical and the commercially viable, and although practical uses of sensors in the meat industry remain very limited, significant practical steps towards more widespread use have been made (Kerry & Papkovsky, 2002). High development and production costs, strict industry specifications, safety considerations and relatively limited demand (in comparison with the biomedical sector) from either

industry or consumer, have so far proved the main obstacles to commercial use. Very few systems to date have been able to match exacting industry standards required for successful application. However, developments in materials science, continuous automation processes, signal processing and process control, along with transfer of technology from the biomedical, environmental and chemical sectors all lead towards the likelihood of more universal adoption of sensor technology in food packaging. Greater pressure on food manufacturers to guarantee safety, quality and traceability is also likely to promote the establishment of commercial sensor technology in food packaging.

4.10.1 Gas Sensors

Gas sensors are devices that respond reversibly and quantitatively to the presence of a gaseous analyte by changing the physical parameters of the sensor which are, in turn, monitored by an external device. Systems presently available for gas detection include amperometric O_2 sensors, potentiometric CO_2 sensors, metal oxide semiconductor field effect transistors, organic conducting polymers and piezoelectric crystal sensors (Kress-Rogers, 1998b). Conventional systems for O_2 sensors based on electrochemical methods have a number of limitations (Trettnak, Gruber, Reininger, & Klimant, 1995). These include factors such as consumption of analyte (O_2), cross-sensitivity to CO_2, hydrogen sulphide and fouling of sensor membranes (Gnaiger & Forstner, 1983). Often, such systems also involve destructive analysis of packages.

In previous years, a number of instruments and materials for optical O_2 sensing have been described (Papkovsky, Ponomarev, Trettnak, & O'Leary, 1995; Thompson & Lakowicz, 1993; Trettnak, et al., 1995). Such sensors are usually comprised of a solid-state material, which operate on the principle of luminescence quenching or absorbance changes caused by direct contact with the analyte. Such systems provide a non-invasive technique for gas analysis through translucent materials and as such are potentially suitable for intelligent packaging applications. The solid-state sensor is inert and does not consume analyte or undergo other chemical reactions (Wolfbeis, 1991). Optochemical sensors have the potential to enhance quality control systems through detection of product deterioration or microbial contamination by sensing gas analytes such as hydrogen sulphide, CO_2 and NH_3 (Wolfbeis & List, 1995).

Approaches to optochemical sensing have included; 1) a fluorescence-based system using a pH-sensitive indicator (Wolfbeis, Weis, Leiner, & Ziegler, 1988); 2) absorption-based colorimetric sensing realised through a visual indicator (Mills, Chang, & McMurray, 1992); and 3) an energy transfer approach using phase fluorimetric detection (Neurauter, Klimant, & Wolfbeis, 1999). The latter allows for the possibility of combining O_2 and CO_2 measurements in a single sensor through compatibility with previously developed O_2 sensing technology. Most CO_2 sensors, however, have been developed for biomedical applications and the potential use of existing CO_2 sensors to be used for food packaging applications is still somewhat distant (Kerry & Papkovsky, 2002).

4.10.2 Fluorescent-based Oxygen Sensors

Fluorescence-based O_2 sensors represent the most advanced and promising systems to date for remote measurement of headspace gases in packaged meat products. Reininger, Kolle, Trettnak, & Gruber (1996) first introduced the concept of using luminescent dyes quenched by O_2 as non-destructive indicators in food packaging applications. A number of O_2 sensing prototypes have been developed and are expected to appear in large-scale commercial applications in the near future. These sensors can be produced cheaply, are disposable and, when used in conjunction with accurate instrumentation, provide rapid determination of O_2 concentration (Kerry & Papkovsky, 2002).

The active component of a fluorescence-based O_2 sensor normally consists of a long-delay fluorescent or phosphorescent dye encapsulated in a solid polymer matrix. The dye-polymer coating is applied as a thin film coating on a suitable solid support (Wolfbeis, 1991). Molecular O_2, present in the packaging headspace, penetrates the sensitive coating through simple diffusion and quenches luminescence by a dynamic (i.e. collisional) mechanism. O_2 is quantified by measuring changes in luminescence parameters from the O_2-sensing element in contact with the gas or liquid sample, using a pre-determined calibration. The process is reversible and clean: neither the dye nor O_2 is consumed in the photochemical reactions involved, no by-products are generated, and the whole cycle can be repeated.

Materials for O_2 sensors must meet strict sensitivity and working performance requirements if they are to prove suitable for commercial intelligent packaging applications. They must also have fluorescent characteristics suited to the construction of simple measuring devices. Fluorescence and phosphorescence dyes with lifetimes in the microsecond range are best suited to O_2 sensing in food packaging. Other necessary features include; suitable intensity, well resolved excitation and emission long-wave bands and good photostability characteristics of the indicator dye. Such features allow sensor compatibility with simple and inexpensive optoelectronic measuring devices (light-emitting diodes, photodiodes etc), minimise interference by scattering and sample fluorescence and allow long-term operation without recalibration (Papkovsky, 1995). Materials using fluorescent complexes of ruthenium, phosphorescent palladium(II)- and platinum(II)-porphyrin complexes and related structures have shown promise as O_2 sensors (Papkovsky, 1995; Papkovsky, Olah, Troyanovsky, Sadovsky, Rumyantseva, Mironov, Yaropolov, & Savitsky, 1992; Wolfbeis, 1991). Subsequent work on phosphorescent complexes of porphyrin-ketones elucidated favourable sensing properties such as high stability, water insolubility, non-volatility and low toxicity (Papkovsky, 1995).

The combination of indicator dye and the encapsulating polymer medium in which O_2 quenching occurs determines the sensitivity and effective working range of such sensors. For the purposes of food packaging applications, dyes with relatively long emission lifetimes (~ 40-500 μs), such as Pt-porphyrins combined with polystyrene as polymer matrix, appear to offer the greatest potential (Papkovsky, Papkovskaia, Smyth, Kerry, & Ogurtsov, 2000; Wolfbeis & List, 1995). Sensors on microporous support materials

(Papkovsky, Ovchinnikov, Ogurtsov, Ponomarev, & Korpela, 1998) also provide a number of unique features for special sensing applications including those applicable to food packaging systems. Other polymers with good gas-barrier properties such as polyamide, polyethylene terephthalate and PVC are not suitable for O_2 sensing as O_2 quenching is slow in such media (Comyn, 1985). The use of plasticised polymers is also unsuitable due to toxicity concerns associated with potential plasticiser migration.

Sensor fabrication involves a simple process of dissolution of lipophilic indicator dye and appropriate polymer support in an organic solvent. This cocktail is applied to a solid substrate, such as a polyester film or glass, and allowed to dry to produce a fluorescent film coating or spot. A number of coating techniques that lend themselves to large scale, continuous production (casting, dipping, spin coating, drop dispensing and spraying) offer possibilities for commercial production. Relatively high concentrations of indicator dye are used to obtain high fluorescence signals. Sensors, normally 1-2 cm in diameter, are coloured (due to the dye) and are readily visible on different support materials.

Oxygen sensor active elements can be manufactured on a large scale using relatively inexpensive materials and equipment. They are robust, suitable for long term/continuous monitoring and can be disposed of easily. Such materials have been successfully used in a variety of non-food applications. In order to ensure successful commercial uptake in food packaging a number of practical criteria must be considered:

- **Working range**: Most O_2 sensors work effectively within two orders of O_2 concentration (and in some cases more). Most of the sensors described work within the range from 0 to 100 kPa of O_2, or at least 0 to 21 kPa (0 to 21%) with detection limits of 0.01 to 0.1 kPa (where, in simple terms, kPa corresponds to percentage O_2 pressure [at room temperature and ambient air pressure]). In general, such working ranges are suitable for most meat packaging applications and MAP in particular.

- **Temperature dependence**: Sensors for food packaging applications are required to operate over a wide temperature range (approximately -20 to +30°C). A lack of systematic and comparative data exists on the behaviour of O_2 sensors over such wide temperature ranges with few studies having addressed this issue (Papkovsky, et al., 2000). Further research is required to ensure the effectiveness of such systems under all meat storage and distribution conditions.

- **Response**: The use of thin film coatings for the sensing material results in low diffusion barrier properties and very fast sensor responses to changes in O_2 concentration – in some case as low as tenths of milliseconds (Kolle, Gruber, Trettnak, Biebernik, Dolezal, Reiniger, & O'Leary, 1997). This feature is important for real-time, on-line quality control of large volume throughput of packages. Such rapid screening allows for immediate identification of improperly sealed units and their removal.

- **Stability**: Sensors incorporated into meat packages are required to remain operable and reliable from the point of packaging to the point of opening. In the

case of the chilled storage of fresh meat products this can be up to several weeks duration, and often longer for frozen storage. Exposure to light, including UV/retail display lighting can cause gradual photobleaching of certain dyes or ageing of polymers. In the case of phase fluorimetric O_2 sensors this is not important but can be problematical for other sensor types.

- **Intrinsic toxicity**: Sensor materials (i.e. dyes, polymers, residual solvents and additives) are the main cause for concern in terms of potential toxicity issues. In general, the total quantity required to produce a single pack sensor is normally less than 1 mg, of which the encapsulating polymer represents > 95%. The amount of dye per sensor usually varies to within a few micrograms. For most organic dyes, such quantities are far below established toxicity levels. It is advisable that solvents normally used in the food industry be used in sensor manufacture in order to avoid dangers associated with residual solvents. O'Riordan, Voraberger, Kerry, & Papkovsky (2005) examined the migration of active components of two metalloporphyrin and one ruthenium dye-based O_2 sensors and established their stability, safety and suitability for large scale use in food packaging applications.

Other recent publications on the suitability of fluorescence based O_2 sensors have provided much useful data on their effectiveness in meat packaging applications. Fitzgerald, Papkovsky, Smiddy, Kerry, O'Sullivan, Buckley, & Guilbault (2001) examined the potential of platinum based disposable O_2 sensors as a quality control instrument for vacuum-packed raw and cooked meat and MAP sliced ham. Direct contact of sensors on the foods provided accurate O_2 profiles over time and correlated well with conventional (i.e. destructive) headspace analysis. Smiddy, Papkovskaia, Papkovsky, & Kerry (2002) used O_2 sensors to examine the effects of residual O_2 concentration on lipid oxidation in both anaerobically MAP and vacuum-packed cooked chicken and in raw and cooked beef (Smiddy, Fitzgerald, Kerry, Papkovsky, O'sullivan, & Guilbault, 2002). These studies further demonstrated the suitability of such sensors to measure non-destructively O_2 levels in commercially used meat packaging and their potential as predictors of quality in processed muscle foods. Papkovsky, Smiddy, Papkovskaia, & Kerry (2002) used O_2 sensors to measure O_2 content in the headspace of four commercial sliced ham products. Accurate measurements were made under ambient light conditions, in direct contact with the product and under conditions of significant temperature variation. Although the sensor demonstrated minor changes in calibration as a result of direct physical contact with the meat surface over a prolonged period, these effects were minimised through optimisation of the sensor material. It is unlikely, in any case, that the presence of sensors in direct contact with a meat product would be acceptable to either producer or consumer. O'Mahony, O'Riordan, Papkovskaia, Ogurtsov, Kerry, & Papkovsky (2004) used fluorescent O_2 sensors printed directly onto the packaging material of *sous vide* beef lasagne and established a clear correlation between O_2 profiles, microbial growth and lipid oxidation. Fluorescent O_2 sensors are also useful in detecting the substantial fraction of commercial anaerobic MAP or vacuum packed meat products containing elevated levels of O_2 (Papkovsky et al., 2002; Smiddy, Papkovsky, & Kerry, 2002).

The development of O_2 sensors outlined above is indicative of the move towards commercialisation of indicator-type smart packaging. The result, given the viable outcome of future research initiatives, may ultimately see the incorporation of sensors in every meat pack produced. Such a scenario would mean the production of millions of sensors and thousands of measurement devices at different points in the production and distribution chain. It has been estimated that in today's terms, each sensor should cost less than one cent to produce (Kerry & Papkovsky, 2002) and impact minimally on packaged meat production costs.

Figure 6. The Optitech™ OxySense® developed by LUXEL Biosences Ltd, University College Cork and MOCON, USA

OxySense® (OxySense website: www.oxysense.com) is the first commercially available fluorescence quenching sensor system for measurement of headspace or dissolved O_2 in transparent or semi-transparent, sealed packages (see Figure 6). The system uses an O_2 sensor (O_2xyDot™) placed in the package before filling and is non-destructive, rapid (measurements take less than five seconds) and able to withstand pasteurisation temperatures without loss of sensitivity. Two new analytical techniques, the GreenLight™ system for rapid enumeration of total viable counts (TVC) in food homogenates and the Optech™ system for non-destructive sensing of residual O_2 in package headspaces are all based on fluorescence-type O_2 sensing and have been developed through research conducted within UCC and commercialised by LUXEL Biosciences (Ireland) and MOCON (USA).

4.10.3 Biosensors

Other approaches to freshness indication, which may be more likely to find commercial application in smart muscle-based food product packaging systems are those based on recently developed biosensor technologies. Biosensors are compact analytical devices that detect, record and transmit information pertaining to biological reactions (Yam, Takhistov, & Miltz, 2005). These devices consist of a bioreceptor specific to a target analyte and a transducer to convert biological signals to a quantifiable electrical response.

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Bioreceptors are organic materials such as enzymes, antigens, microbes, hormones and nucleic acids. Transducers may be electrochemical, optical, calorimetric etc, and are system dependent. Smart or intelligent packaging systems incorporating biosensors have the potential for extreme specificity and reliability. Market analysis of pathogen detection and safety systems for the food packaging industry suggests that biosensors offer considerable promise for future growth (Alocilja & Radke, 2003).

The majority of available biosensor technology is not yet capable of commercial realisation in the food sector. However, a significant number of commercially available biosensor and/or indicator systems have already been developed; FreshTag (Cox Recorders, USA), FreshQ (Food Quality Sensor International Inc., USA) SensorQ (DSM NV Global and Food Quality Sensor International Inc., USA), CO_2 detectors (Sealed Air, USA), Transia test strips (Transia GmbH, Germany), Freshness Guard Indicator or Raflatac (UPM Raflatac, Finland), It's Fresh[TM] (It's Fresh Inc., USA), ToxinGuard[TM] (Toxin Alert Inc., Canada) and Food Sentinel SystemTM (Sira Technologies, USA: See Figure 7) (Smolander, 2008). The more recently developed ToxinGuard[TM] is a visual diagnostic system that incorporates antibodies in a polyethylene-based plastic packaging capable of detecting *Salmonella sp*., *Campylobacter sp*., *E. coli 0517* and *Listeria sp*. (Bodenhamer, 2002; Bodenhamer, Jackowski, & Davies, 2004). Another recent development is the Food Sentinel System[TM] (SIRA Technologies, California, USA) which is a biosensor system capable of continuous detection of contamination through immunological reactions occurring in part of a barcode. The barcode is rendered unreadable by the presence of contaminating bacteria. Such systems give some insight into products likely to become more popular in the years to come.

Figure 7. The SIRA Technologies Inc. Food Sentinel System™ whereby contaminating bacteria render the barcode unreadable.

4.11 Indicators

An indicator may be defined as a substance that indicates, in the presence or absence of another substance or the degree of reaction between two or more substances by means of a characteristic change, especially in colour. In contrast with sensors, indicators do not comprise receptor and transducer components and communicate information through direct visual change (see commercial examples provided previously).

4.11.1 Integrity Indicators

An alternative approach to such package-destructive techniques is the use of non-invasive indicator systems as part of MAP. Such systems usually provide qualitative or semi-quantitative information through visual colorimetric changes or through comparison with standard references. The majority of indicators have been developed for package integrity testing, an essential requirement for the maintenance of quality and safety standards in packaging of muscle or muscle-based products. The most common cause of integrity damage in flexible plastic packages is associated with leaking seals (Hurme, 2003). Permanent attachment of a leak indicator or sensor (i.e. visual or optochemical) to a package appears to hold most promise in ensuring package integrity throughout the production and distribution chain. A number of studies on package integrity in MAP meat products (Ahvenainen, Eilamo, & Hurme, 1997; Eilamo, Ahvenainen, Hurme, Heiniö, & Mattila-Sandholm, 1995; Randell, Ahvenainen, Latva-Kala, Hurme, Mattila-Sandholm, & Hyvönen, 1995) have established critical leak sizes and associated quality deterioration. Although a number of destructive manual methods are available for package integrity and leak testing such tests are laborious and can test only limited numbers of packs (Hurme, 2003). Available non-destructive detection systems (which include a number of stimulus response techniques) have other disadvantages such as the need for specialised equipment, slow sampling time and an inability to detect leakages that are penetrable by pathogens (Hurme & Ahvenainen, 1998; Stauffer, 1988).

Much work on the development of integrity detection for packaged foods has focused on visual O_2 indicators in MAP foods (as opposed to those O_2 sensors previously discussed, which are also applicable to integrity testing). With the exception of high O_2 content MAP for fresh meat (primarily to enhance colour) many foods are packaged in low (0-2%) O_2 atmospheres. In such cases, leaks normally result in a significant increase in O_2 concentration. Many visual O_2 indicators consisting mainly of a redox dyes have been patented (Davies & Gardner, 1996; Krumhar & Karel, 1992; Mattila-Sandholm, Ahvenainen, Hurme, & Järvi-Kääriänen, 1995; Yoshikawa, Nawata, Goto, & Fujii, 1987). Such devices have been tested as leak indicators in MAP minced steaks and minced meat pizzas respectively and reported as reliable (Ahvenainen, et al., 1997; Eilamo, et al., 1995). Disadvantages of such devices include high sensitivity (approximately 0.1% O_2 concentration required for colour change means indicators are susceptible to residual O_2 in MAP) and reversibility (undesirable where increased O_2 due to a leak is consumed during subsequent microbial growth). Few of these devices have been taken up commercially. One indicator system, specifically designed for MAP foods contains, in

addition to an O_2 sensitive dye, an O_2 absorbing component and exemplifies active and intelligent packaging in a single system (Mattila-Sandholm, et al., 1995).

A number of companies have produced O_2 indicators, the main application of which has been for the confirmation of proper functioning of O_2 absorbers (an active packaging function). Trade names of such devices have included; Ageless Eye[®], Vitalon[®], and Samso-Checker[®] (Smolander, Hurme, & Ahvenainen, 1997). A visual CO_2 indicator system consisting of calcium hydroxide (CO_2 absorber) and a redox indicator dye incorporated in polypropylene resin has been described Hong & Park (2000) and may be applicable to certain meat packaging applications.

4.11.2 Integrity and Freshness Indicators

The information provided by intelligent packaging systems on the quality of meat products may be either indirect (e.g. changes in packaging O_2 concentration may imply quality deterioration through established correlation) or direct. Freshness indicators provide direct product quality information resulting from microbial growth or chemical changes within a food product. Microbiological quality may be determined through reactions between indicators included within the package and microbial growth metabolites (Smolander, 2008). As yet, the number of practical concepts of intelligent package indicators for freshness detection is limited, but has increased dramatically over the past five years or so with products such as Timestrip[®] (Timestrip Ltd., UK), Novas[®] (Insignia Technologies Ltd., UK), BestBy[®] (Freshpoint, Switzerland) and Tell-Tab (IMPAK Corporation, USA). Despite this, considerable potential exists for the development of freshness indicators based on established knowledge of quality indicating metabolites. The chemical detection of spoilage of foods (Dainty, 1996) and the chemical changes in meat during storage (Nychas, Drosinos, & Board, 1998) provide the basis for which freshness indicators may be developed based on target metabolites associated with microbiologically-induced deterioration. Using the marker concept in this manner may result in the more widespread commercial development of freshness indicators for meat products in the not too distant future.

The formation of different potential indicator metabolites in meat products is dependent on the product type, associated spoilage flora, storage conditions and packaging system. A number of marker metabolites associated with muscle food products exist upon which indicator development may be based;

- Changes in the concentration of organic acids such as n-butyrate, L-lactic acid, D-lactate and acetic acid during storage offer potential as indicator metabolites for a number of meat products (Shu, Hakanson, & Mattiasson, 1993). Colour based pH indicators offer potential for use as indicators of these microbial metabolites.

- Ethanol, like lactic acid and acetic acid, is an important indicator of fermentative metabolism of lactic acid bacteria. Randell, et al. (1995) reported

an increase in the ethanol concentration of anaerobically MAP marinated chicken as a function of storage time.

- Volatile compounds (e.g. TMA, dimethylamine and N_2 (collectively described as TVB-N) or the biogenic NH_3 such as histamine, hypoxanthine, putrescine, tyramine and cadaverine) have been implicated as indicators of muscle-based product decomposition (Kaniou, Samouris, Mouratidou, Eleftheriadou, & Zantopoulos, 2001; Okuma, Okazaki, Usami, & Horikoshi, 2000; Rokka, Eerola, Smolander, Alakomi, & Ahvenainen, 2004; Taoukis, Koutsoumanis, & Nychas, 1999). Given toxicological concerns associated with these compounds and their lack of impact on sensory quality, the development of effective NH_3 indicators would be of benefit. Detection systems described by Miller, Wilkes, & Conte (1999), and Loughran, & Diamond (2000) provide potential for commercial development. In 1999, COX Technologies (USA), launched FreshTag® colour change indicator labels that react to volatile NH_3 produced during storage of fish and other seafood. The ownership of this interesting technology moved from COX Technologies to Sensitech in 2004 and then to Carrier Corporation, none of which has assisted the further development or commercialisation of the technology. Research on a sensor technology similar to the FreshTag® technology is currently under development by the Adaptive Sensor Group in Dublin City University (Pacquit, et al., 2008).

- CO_2 produced during microbial growth can in many instances be indicative of quality deterioration. In MAP meat products containing high CO_2 concentration (typically 20-80%), indication of microbial growth by changes in CO_2 content is problematical, although application of pH dye indicators may hold promise in other meat packaging systems.

- Hydrogen sulphide, a breakdown product of cysteine, with intense off-flavours and low threshold levels is produced during the spoilage of meat, poultry and seafood by a number of bacterial species. It forms a green pigment, sulphmyocin, when bound to myoglobin and this pigment formed the basis for the development of an agarose-immobilised, myoglobin-based freshness indicator in unmarinated broiler pieces (Smolander, Hurme, Latva-Kala, Luoma, Alakomi, & Ahvenainen, 2002). The indicator was not affected by the presence of N_2 or CO_2 and offers potential.

A variety of different types of freshness indicators have been described (Smolander, 2008; Smolander & Ahvenainen, 2003) the majority of which are based on indicator colour change in response to microbial metabolites produced during spoilage (Figure 8). Freshness indicators based on broad spectrum colour changes have a number of disadvantages which need to be resolved before widespread commercial uptake is likely. A lack of specificity means that colour changes indicating contamination can occur in products free from any significant sensory or microbiological quality deterioration. The presence of certain target metabolites is not necessarily an indication of poor quality. More exact correlations appear necessary between target metabolite, product type and organoleptic quality and safety. The possibilities of false-negatives are likely to dissuade

producers from adopting indicators unless specific indication of actual spoilage can be guaranteed.

Figure 8. Examples of freshness indicators from (a) RAFLATAC® and (b) Insignia Technologies: UK (Smolander, 2008)

4.11.3 Time-Temperature Indicators

A time temperature indicator or integrator (TTI) may be defined as a device used to show a measurable, time-temperature dependent change that reflects the full or partial temperature history of a food product to which it is attached (Taoukis & Labuza, 1989). Operation of TTIs is based on mechanical, chemical, electrochemical, enzymatic or microbiological change, usually expressed as a visible response in the form of a mechanical deformation, colour development or colour movement (Taoukis & Labuza, 2003). The visible response thus gives a cumulative indication of the storage temperature to which the TTI has been exposed. TTIs may be classified as either partial history or full history indicators, depending on their response mechanism. Partial history indicators do not respond unless a temperature threshold has been exceeded and indicate that a product has been exposed to a temperature sufficient to cause a change in product quality or safety. Full history TTIs give a continuous temperature-dependent response throughout a products history and constitute the main focus of interest for research and commercial exploitation.

Essentially TTIs are small tags or labels that keep track of time-temperature histories to which a perishable product is exposed from the point of manufacture to the retail outlet or end-consumer (Fu & Labuza, 1995). Their use in meat, poultry and seafood products,

where monitoring of the cold distribution chain, microbial safety and quality are of paramount importance, offers enormous potential.

The basic requirement of an effective TTI is to indicate clear, continuous, irreversible reaction to changes in temperature. Ideally, TTIs should also be low cost, small, reliable, easily integrated into food packaging, have a long pre- and post-activation shelf life and be unaffected by ambient conditions other than temperature. TTIs should also be flexible to a range of temperatures, robust, pose no toxicological or safety hazard and convey information in a clear manner.

A large number of TTI types have been developed and patented, and the principles and applications have been reviewed previously (Fu & Labuza, 1995; Selman, 1995; Taoukis, 2008; Taoukis & Labuza, 2003). TTIs currently commercially available include a number of diffusion, enzymatic and polymer-based systems, all of which offer potential for use in muscle-based food products.

4.11.4 Diffusion-based Time-Temperature Indicators

The 3M Monitor Mark® (3M Company, St. Paul, Minnesota, USA) is an indicator dependent on the diffusion of a coloured fatty acid ester along a porous wick made of high quality blotting paper. The measurable response is the distance of the advancing diffusion front from the origin. The useful range of temperatures and the response life of the TTI are determined by the type and concentration of ester. Another diffusion-based TTI, Fresh-Check®, produced by the same company incorporates a viscoelastic material that migrates into a diffusively light-reflective porous matrix at a temperature dependent rate. This causes a progressive change in the light transmissivity of the porous matrix and provides a visual response. The TT Sensor® (Avery Dennison Corporation, USA: Figure 9), again based on diffusion-reaction, allows for the diffusion of a polar compound between two polymer layers and the change in its concentration causes the colour change of a fluorescent indicator from yellow to bright pink (Taoukis, 2008). The Keep-it (Keep-it Technologies, Norway) TTI similarly indicates temperature abuse as indicated by a blue strip moving from left to right in the indicator. The Keep-it TTI contains two chambers with different ingredients which react to both time and temperature. The indicator is activated when the chamber is opened so that the chemicals react with each other. Activation of the indicator is carried out by the manufacturer at the point of product packing.

Figure 9. The TT Sensor™ diffusion-reaction Time-Temperature Indicator (Avery Dennison Corp.: USA).

4.11.5 Enzymatic Time-Temperature Indicators

The CheckPoint® or VITSAB® TTI (VITSAB A.B., Malmö, Sweden) is based on a colour change induced by a drop in pH resulting from the controlled enzymatic hydrolysis of a lipid substrate (Figure 10). The indicator consists of two separate compartments containing an aqueous solution of lipolytic enzymes and another containing the lipid substrate suspended in an aqueous medium and a pH indicator mix. Different enzyme–substrate combinations are available to give a variety of response lives and temperature dependencies. Activation of the TTI is brought about by mechanical breakage of a seal separating the two compartments and may be done manually or by on-line automation. Hydrolysis of the substrate causes a drop in pH and a subsequent colour change in the pH indicator from dark green to bright yellow. Visual evaluation of the colour change is made by reference to a five-point colour scale. CheckPoint® labels are the latest TTIs developed by VITSAB, which comprise a label type designed to create a better subjective reading response for users and offer direct application to seafood, poultry and ground beef products. VITSAB, in conjunction with British Airways, has also developed a TTI system (Flight 17 Smart Label) that allows airline personnel to check the status of perishable pre-prepared foods.

Figure 10. The CheckPoint® Time-Temperature Indicator which suggests 'do not use if the circle is pink' (Vistsab International: Sweden)

The eO® (CRYOLOG, France) adhesive TTI label takes the form of a flower-shaped gel pad which changes from green (good) to red (not good). The colour change is pH induced and caused by microbial growth within the gel itself. The TRACEO® (TRACEO, France) transparent label is designed for use on refrigerated products and placed over the barcode. The colour of the transparent adhesive label changes from colourless to red when the product is no longer fit for consumption (O'Grady & Kerry, 2008). The TopCryo® (TRACEO, France) functions similarly to the original TRACEO technology, but operates on a colour change from green to red.

4.11.6 Polymer-based Time-Temperature Indicators

Lifelines Freshness Monitor® and Fresh-Check TTIs (Lifelines Technology Inc., Morris Plains, New Jersey, USA) are based on temperature dependent polymerisation reactions in which diacetylene crystals polymerise via 1,4 addition polymerisation to a highly coloured polymer. Resulting changes in reflectance can be measured by scanning with a laser optic wand. The Fresh-Check® consumer version uses a circular label in which the colour of the inner circle is compared to that of an outer circle in order to establish use-by status.

The OnVu™ TTI labels (Ciba Specialty Chemicals Inc., Switzerland) are based on organic pigments which change colour with time at rates determined by temperature. The TTI label consists of a heart-shaped apple motif containing an inner heart shape. The image is stable until activated by UV light from a LED lamp, which in turn causes the inner heart shape to become deep blue in colour. A filter is then added over the label to prevent it from becoming recharged. The inner blue heart changes to white as a function of both time and temperature. This system can be applied as a label or printed directly onto the package (O'Grady & Kerry, 2008).

Quite separately, TTIs have been recently developed, but which indicate through changes in the barcoding present on packs. The FreshCode™ (VARCODE, Israel and USA) smart barcode labels are a novel TTI technology. By combining temperature measurement into the data value of the barcode, VARCODE has developed a low-cost, but data-rich and easy-to-use solution for monitoring the cold chain. The FreshCode™ label is based on a chemical process that triggers a value change in the displayed barcode whenever any of the multiple pre-set events occurs. The label is designed to start its monitoring process activated by pulling a tab, therefore, no special storage is required. The label can be read in as many check points throughout the cold chain as required, from the point of activation all the way up to the retail cashier. These smart barcodes can be read by any commonly used barcode reader as well as iOS or Android based smart phones and tablets. The use of a standard barcode reader ensures not only fast and accurate reading, but smooth integration into the enterprise's existing procedures with no need for equipment purchase or any other investment (VARCODE web page: www.varcode.com). Similarly, the Tempix® (TEMPIX AB, Sweden) TTI functions similarly to the previously described technology, as it too indicates muscle-based food product quality through changes in the barcoding as the product moves along the cold chain. If the cold chain has

been broken or the product in question is temperature abused, all of this will be reflected by the presence of additional bars on the pack barcoding label.

Initial expectations on the potential of TTIs to contribute to improved standards in food distribution, quality and safety have not been realised to date. Factors such as cost, reliability and applicability have all been influential in this regard. The cost of TTIs has been estimated at approximately $0.02 to $0.20 per unit (Taoukis & Labuza, 2003). Given normal economies of scale, cost-benefit analysis should favour more widespread use of TTIs. Faith in the reliability of TTIs has been undermined somewhat by insufficient supporting data. It appears now that TTI systems have achieved high standards of production and quality assurance and provide reliable and reproducible responses according to BSI specifications (BSI, 1999). The most substantial hurdle to extensive commercial TTI use has been the question of applicability. Generalisations on the relationship between temperature and quality of general food classes have proved insufficient, as even foods of similar type differ markedly in terms of response. For successful application of TTIs to meat, poultry and seafood products, and food products in general, there is a requirement that the TTI response matches the behaviour of the food. Whilst the expectation for a TTI to strictly match the behaviour of a foodstuff over a wide temperature range is unfeasible, a thorough knowledge of the shelf-life loss behaviour of a food system based on accurate kinetic models is essential (Taoukis & Labuza, 2003) and advances in food modelling are making this possible (Taoukis, 2001).

A number of validation studies have been undertaken in order to establish the usefulness of TTIs in food products (Riva, Piergiovanni, & Schiraldi, 2001; Shimoni, Anderson, & Labuza, 2001; Welt, Sage, & Berger, 2003). Yoon, Lee, Kim, Kim, & Park (1994) showed a positive correlation between oxidative stability and TTI colour change using a phospholipid/phospholipase-based TTI in frozen pork. Smolander, Alakomi, Ritvanen, Vainionpää, & Ahvenainen (2004) and Vainionpää, Smolander, Alakomi, Ritvanen, Rajamäki, Rokka, & Ahvenainen (2004) determined the applicability of VITSAB®, Fresh-Check® and 3M Monitor® TTIs for monitoring the quality of MAP broiler cuts at different temperatures and in comparison with several standard analytical methods respectively. Otwell (1997) also assessed the VITSAB® TTI in MAP salmon. In all three studies, TTIs were closely correlated with microbiological analyses of spoilage bacteria and in some cases, were shown to be more effective than certain metabolic quality indices such as spoilage-associated volatiles, biogenic NH_3 and organic acids. Pacquit et al. (2008) highlighted the fact that commercial trials have been conducted for seafood products, primarily salmon products, using TTI Sensor™, Fresh-Check® and Checkpoint® TTI technologies.

In 1991 a UK survey (Harris, 1991) indicated that 95% of respondents (n = 511) considered TTIs to be a good idea, but indicated that substantial publicity or an educational campaign would be required for general use. It is likely that such attitudes still apply today. Despite predictions for the full commercial realisation of TTIs, adoption has been very limited. However, given technological developments in recent years, greater consumer appreciation for the need for food safety monitoring (particularly in muscle-based products) and the growing legislative demand for guaranteed food safety; analysts believe that TTIs will inevitably find widespread commercial application in the food

industry. The critical importance of maintaining proper storage temperatures for meat and poultry products throughout the distribution chain means that this sector of the food industry could be a major beneficiary from such a development.

4.12 Radio Frequency Identification Tags

Radio frequency identification tags (RFID) technology does not fall into either sensor or indicator classification, but rather represents a separate electronic information based form of intelligent packaging. RFID uses tags affixed to assets (cattle, containers, pallets etc) to transmit accurate, real-time information to a user's information system. RFID is one of the many automatic-identification technologies (a group which includes barcodes) and offers a number of potential benefits to the meat production, distribution and retail chain. These include traceability, inventory management, labour saving costs, security and promotion of quality and safety (Mousavi, Sarhadi, Lenk, & Fawcett, 2002). Prevention of product recalls is also considered an important role of RFID technology (Kumar & Budin, 2006). RFID technology has been available for approximately 40 years although its broad application in packaging is a relatively recent development.

At its most basic level, an RFID tag contains a tiny transponder and antenna that have a unique number or alphanumerical sequence; the tag responds to signals received from a reader's antenna and transmits its number back to the reader (Figure 11). While the tags are relatively simple, much better inventory information than barcode or human entry systems can be gained through tracking software. RFID tags have the advantage over barcoding in that tags can be embedded within a container or package without adversely affecting the data. RFID tags also provide a non-contact, non-line-of-sight ability to gather real-time data and can penetrate non-metallic materials, for instance bio-matter (Mennecke & Townsend, 2005). RFID tags can hold simple information (such as identification numbers) for tracking or can carry more complex information (with storage capacity at present up to about 1 MB) such as temperature and relative humidity data, nutritional information, source/origin, key processing dates and times, cooking instructions etc. Read-only and read/write tags are also available depending on the requirements of the application in question.

Figure 11. An example of a Radio Frequency Identification Tag (RFID).

Tags can be classified according to two types: 1) Active tags which function with battery power, broadcast a signal to the RFID reader and operate at a distance of up to approximately 50 meters; 2) Passive tags have a shorter reading range (up to

approximately 5 meters) and are powered by the energy supplied by the reader (giving them essentially unlimited life).

Common RFID frequencies range from low (approximately 125 KHz) to UHF (850-900 MHz) and microwave frequencies (approximately 2.45 GHz). Low frequency 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.

The costs of RFID are decreasing rapidly as major companies such as Wal-Mart, 7-Eleven and Marks & Spencers adopt the technology. At present, the cost of passive RFID tags range from approximately $0.50 to $1.00. For the technology to be truly competitive, these tags must cost less than $0.05 (others below $0.01) (Want, 2004) and it is expected that costs will fall to the $0.01 per-tag level in due course (Mennecke & Townsend, 2005). Initiatives to establish formal standards should also serve to reduce further the cost of RFID systems.

RFID is beginning to be used in a number of countries for tracing individual animals (mainly cattle) from birth to the processing plant. The key to individual animal traceability lies in the ability to transfer animal information sequentially and accurately to sub-parts of the animal during production. RFID-based tracking systems provide an automated method of contributing significantly to that information exchange (Townsend & Mennecke, 2008). At present, individually RFID tagged muscle-based food products are not available to the consumer (to the best of the our knowledge), although the use of RFID tagging of meat cuts has extended, in one case at least, in the pig processing industry from the individual pig to its' primal pieces (i.e. hams). Hedgepeth (2005) outlined how RFID tags were being employed on pallets of fish exported from Alaska as a means of verifying origin, storage and transportation. SINTEF conducted trials in Norway to monitor the controlled movement of super-chilled lamb from slaughter through to retail storage using RFID. Although the purpose of these tracking schemes is for quality control, traceability and accountability; it does exemplify the developing use of RFID technology within the muscle-based food industry. Although the implementation of intelligent packaging of meat, poultry and seafood products using RFID technology is still largely hypothetical, current indications suggest it is unlikely to remain so.

4.13 Advanced Consumer-pack Interaction Systems

Smart cooking is a new cooking innovation combining the cooking capabilities of a convection oven with microwave and grill cooking. The smart cooking process is made possible through the innovation of smart ovens (e.g. Samsung BCE 1197) which have the capacity to read special, on pack SmartCodes (two-dimensional barcodes). The SmartCode is scanned by the built-in oven scanner and the smart oven converts the code into cooking instructions. Every SmartCode contains a unique set of instructions which provide the smart oven with the correct temperature, microwave power and time to cook the food to perfection and consistently (O'Grady & Kerry, 2008). Marks & Spencer's were one

of the first retailing chains to adopt this technology and apply it to a range of muscle-based food products.

With the growing popularity of smart phones, a new phenomenon, and associated with a wide range of fast moving consumer goods, called RC is starting to become popular. Special RC codes are starting to appear on a wide variety of food packs. Consumers can engage much more with the food products in question by scanning RC codes with their smart phones and whole new levels of communication can take place between the consumer and product and between the consumer and product manufacturer. Clearly, this technology could pose some major advantages for those companies producing meat, poultry and seafood products around areas such as; safe handling of product, cooking instructions, presentation of cooking options, recipe ideas, traceability information, animal welfare information and much more.

5.0 Review of Patents

Meat packaging is shifting from its traditional application as an inert barrier against contaminants to encompass complementary functions to improve product quality and longevity. Innovations permitting this advancement have been categorised under the umbrella term of 'smart packaging'. Smart packaging can be further refined into sub-groups, the predominant grouping being intelligent and active packaging (Kerry & Butler, 2008b). Intelligent meat packaging refers to meat packages which monitor and signal meat quality and spoilage, whereas, active packaging functions to counter deteriorative meat processes, thereby enhancing safety and quality attributes. Intelligent packaging has been the focus of many recent innovations and patents, particularly for evaluating product pH, temperature, gaseous concentrations and tracking. Active packaging uses antimicrobial agents, packaging inserts and atmospheric modification to counter oxidation and microbial spoilage. Improved packaging integrity is also a topic for much recent invention. This review outlines some auspicious recent patents in the field of smart packaging and identifies scope for further invention.

5.1 Introduction

Meat packaging is often taken for granted by modern consumers, whom have increasing expectations for meat products and packaging. Many of these expectations are in addition to the four traditional functions of meat packaging, being: 1) protection, wherein O_2, water, UV light and both chemical and microbial contamination are excluded from the packaged contents (Pereira de Abreu, Cruz, & Paseiro Losada, 2012a); 2) communication pertaining to packaging contents, marketability, product attractiveness to retailers and consumers, and design considerations (Walsh & Kerry, 2002); 3) convenience, in terms of product freshness, quality and availability when demanded; and 4) containment, or durability of packaging materials and suitability for either storage or retail display (Yam et al. 2005). The suggested improvements to these fundamentals of meat packaging stem from necessity. For instance, the need to reduce labour inputs at the retail level, the need for a consistently safe product and the need for fresh and high quality meat products in a time-constrained society all pressure change in meat packaging (Belcher, 2006). This change highlights a need to define what constitutes an ideal meat package.

The opinion expressed here is that ideal meat packaging should provide a cost-effective barrier against both biological and chemical hazard, while simultaneously contributing to the longevity of product quality and enhancement in consumer appeal. Meat enhancement by packaging may be via permitted enzymatic activity to promote tenderness or the development of red meat colour to match the cherry-red colour desired by consumers (Kerry et al. 2006; Walsh & Kerry, 2002). It is the enhancement of meat quality by meat packaging which counters other definitions of the role of meat packaging, wherein its sole function is to hold meat quality unchanged when compared with quality immediately prior to packaging (Rooney, 2005). It is the pursuit of ideal meat packaging that led to much focus upon smart packaging development.

Smart packaging, sometimes called innovative packaging, refers to the expansion of packaging functionality beyond traditional roles (Kuswandi et al. 2011). These generally exploit interactions between meat content, packaging environment and package materials rather than relying on packaging to act as an inert barrier (Yam et al. 2005). The classifications of active and intelligent packaging do not always indicate exclusivity; as many of these packaging types have the potential to be jointly applied in the search for ideal meat packaging.

Active packaging deliberately alters its internal conditions via the interference of package materials enhanced by specific additives with package contents to optimise quality, safety and shelf-life (Kerry & Butler, 2008b; Quintavalla & Vicini, 2002). This can involve physical, chemical and/or biological actions influencing interactions between the package materials, packaged meat and package atmosphere to achieve a common goal (Yam et al. 2005). As previously stated, these goals can include meat quality, safety and shelf-life considerations. Intelligent packaging, however, does not directly interact with packaged meat. Instead it monitors and relays information about the quality status and history of a packaged meat (Kerry & Butler, 2008b; Rooney, 2005). This data is then available to retailers and consumers to permit price discrimination and identifications of areas for improvement within the supply chain. Essentially, intelligent packaging is a tool for educated assessment of meat product quality, longevity and marketability (Yam et al. 2005).

The adoption of smart packaging is, however, restricted by current engineering and technological limitations, detrimental environmental and economic effects, and unforseen parallel by-products or side-effects on meat quality and manufacture time (Rooney, 2005). Overcoming these limitations is the priority of inventors from diverse fields and interests, and is evident when reviewing patents for smart packaging. It is the objective herein to report innovations in smart packaging by reviewing patent literature published since 2012. Consequently, a snapshot overview of current inventions within the field of smart packaging of fresh meat is provided and described within a scientific context regarding implications for quality, safety and shelf-life.

5.2 Packaged Meat Spoilage

The microbial spoilage of packaged meat constitutes a failure for all stakeholders in the meat supply chain. Microbial spoilage can result from either direct microbial growth or the release of microbial enzymes into a packaged meat – with the former generally causing faster spoilage than the latter (Quintavalla & Vicini, 2002). Characteristic microbial spoilage is evident through the development of rancid meat odours and flavours, with discolouration, and gas and slime synthesis being lesser symptoms (Borch, Kant-Muermans, & Blixt, 1996). Nonetheless, all these symptoms arise via the microbial metabolism of carbon and amino acid meat components to facilitate microbial growth and increased spoilage potential (Kerry, 2012). Microbial spoilage is also a function of the microbial flora present within the meat package environment, and the following species have been identified as predominant causal agents: *B. thermosphacta, Carnobacterium*

spp., Enterobacteriaceae, Lactobacillus spp., Leuconostoc spp., Pseudomonas spp. and *S. putrefaciens* (Borch, et al. 1996). As a rule of thumb, microbial population increases result in corresponding increases in packaged meat spoilage and quality downgrades.

Biochemical spoilage refers to the degradation of packaged meat due to non-microbial based factors. Commonly, these are lipid oxidation and autolytic enzymatic spoilage pathways which contribute to the breakdown of meat protein, fat and carbohydrate components which then release by-products that add to further breakdown. Moreover, these by-products cause packaged meat to develop rancid odours and flavours (Dave & Ghaly, 2011). Meat is vulnerable to lipid oxidation as it is a lipid rich substance that can have a high content of unsaturated fats that are prone to oxidation by free radicals (Jos & Veld, 1996), such as those present within a package environment. Any susceptibility, however, is a function of meat antioxidant content – for example vitamin E (Ponnampalam, Norng, Burnett, Dunshea, Jacobs, & Hopkins, 2014). Lipid oxidation can also contribute to meat discolouration (Jos & Veld, 1996) and often acts as an ignition point for protein oxidation and subsequent loss of product integrity (Leygonie, Britz, & Hoffman, 2012). It is through limiting and quantifying meat spoilage that smart packaging contributes to ideal packaging.

5.3 Intelligent Packaging

5.3.1 Gaseous Sensors

To expand on previous statements, gas is a by-product of meat spoilage; hence the change in gaseous concentrations within a package atmosphere can be associated with the extent of spoilage. This relationship provides a means by which many recent intelligent packaging innovations quantify spoilage, generally measuring CO_2, O_2, NH_3 or other gaseous products unique to meat spoilage (Ercolini, Russo, Torrieri, Masi, & Villani, 2006).

The Strahle and Donnet (2012) patent involved the inclusion of a meat package insert, viewable through a clear packaging panel that changes colour as NH_3 concentration within the package atmosphere increases above a predetermined threshold. In many ways this builds upon many past devices which provide visual indication of gas concentration changes (Kuswandi et al. 2011). Yet, the Mills, Gosshans, & Skinner (2012) patent takes this approach and applies similar principles in a unique application. This latter patent describes the impregnation of a plastic substrate with a reactive dye that changes colour as package atmosphere gas concentrations vary. This has the advantage that the plastic substrate can be moulded to comprise the meat package, either as the tray, container or packaging film. Both these innovations rely upon individual manual appraisal to determine spoilage, and thus the labour intensive nature of this approach may prove unviable. Fortunately, remote package atmospheric sensors provide a means to overcome this intrinsic limitation.

Remote atmospheric sensors should be accurate, inexpensive and non-hazardous (i.e. choking hazard), and the Sandvick (2012) patent is aimed at fulfilling these requirements (see Figure 12). It describes a device to be included within meat packages and is comprised of multiple sensors that independently measure factors indicative of meat spoilage before combining this information using an artificial logic algorithm to determine product freshness and safety. This device provides information as a visual change on a three-stage scale and relayed to a central unit. This device is, however, restricted by its reliance on an energy source being included in packaging with the sensor and its cost. The Bridges, Thomson, Bhadra, & Freund (2013) patent describes a remote sensor that can passively transmit information within a wireless network, which allows product appraisal to be made using a central unit or a handheld wireless device (i.e. a smart phone). This device avoids the challenge of including an energy source with a remote sensor.
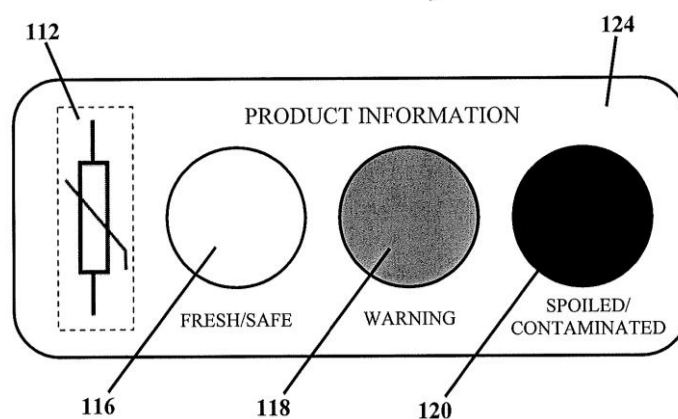
Figure 12. A sensor that provides both a visual and remote indicator of packaged meat quality (Sandvick, 2012)

The Humbert, Gravesteijn, Teunissen, & Bastiaansen (2012) patent uses chemical reactivity to measure package atmospheric gaseous concentrations and presents this information both visually and remotely. This device exploits a change in chemical crystal structure with exposure to particular gas concentrations resulting in a colour change, which can be viewed through a clear packaging panel. It also relays this information using a near-field communication network to an external central unit, therefore allowing retailers and consumers alike to readily evaluate measured information and make informed decisions accordingly.

5.3.2 pH Sensors

Variations in packaged meat pH can prove a valuable marker for product freshness. This is because a spoiled meat product has lower pH. Catalysing this change is the metabolism of glucose that occurs with meat spoilage, and the subsequent synthesis of acetic, isobutyric, lactic and other acidic by-products (Ammor, Tauveron, Dufour, & Chevallier, 2006; Ray & Bhunia, 2013) which occurs within the anaerobic glycolytic pathways (Dave & Ghaly, 2011). Therefore, the concentration of these acidic by-products is reflected by the

extent of spoilage and meat pH (Vaikousi, Biliaderis, & Koutsoumanis, 2009). This relationship has been instrumental for many recent innovations in intelligent packaging.

The Merz, Tak, & Hoofman (2014) patent describes a cost-effective pH sensor that has reference electrodes that can be incorporated within a meat package rather than the device itself (Figure 13). This involves the insertion of a sharp sensor into the packaged meat which then transmits pH information remotely using radio frequency identification (RFID) signals. Unfortunately, these electrodes could be a choking hazard and dangers exist with the 'sharp' sensor inserted within a consumable product. The Chiao & Huang (2013) patent avoids these hazards as the described device is a miniature and flexible pH sensor that can determine and relay measurements using the same RFID system, but only requires contact with the packaged meat surface. Nevertheless, both these devices only offer a remote appraisal of pH, and therefore exclude consumers from having a visual appraisal option.
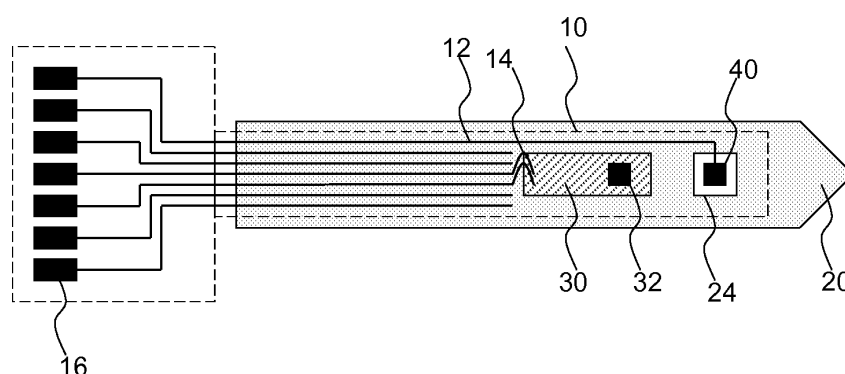
Figure 13. A cost-effective pH sensor/probe with the potential application within meat packaging (Merz et al., 2014)

5.3.3 Biosensors

Because a packaged meat has a high concentration of microbial flora does not intrinsically imply spoilage, and the opposite is also true. As previously described, microbial spoilage of meat is associated with specific bacterial strains; likewise only certain bacteria are pathogenic and potentially harmful to consumers. Hence, intelligent packaging inventors are developing means to qualitatively monitor specific microorganisms. The Bitterly, Bitterly, & Bitterly (2012) patent is one such innovation. This is based on a small (< 1mm^2) disposable microbial load sensor that differentiates microbes by recognition of voltage signal signatures unique to individual metabolic reactions. These devices have the potential for individual inclusion within meat packaging, or numerous inclusions within a

single package. The latter option does offer additional benefit as the numerous sensors can 'link up' and allow better relay of information within a remote network.

The Hu, Murphy, & Stevens (2014) patent defines another biomarker for intelligent packaging, called the 'Bactometer'. This device is inserted into packaged meat and detects the prevalence of lactic acid bacteria by monitoring parallel physicochemical changes. As previously iterated, lactic acid bacteria are significant contributors to microbial meat spoilage. They are anaerobic microbes that metabolise surface glucose until meat reserves are exhausted (Ammor et al., 2006), following which proteins and amino acids are broken-down. This metabolism, especially of sulphur-containing amino acids, can result in the build-up of hydrogen sulphide levels within a meat package which causes the offensive 'rancid' odours and flavours associated with meat spoilage (Borch et al., 1996). Consequently, the ability to qualitatively quantify lactic acid bacteria could provide better insight into microbial meat spoilage.

5.3.4 Temperature Sensors

Temperature is a primary factor influencing meat spoilage rate and degree, with the basic principle that higher temperatures equal higher meat spoilage rates until a threshold level is breached. This is based upon microbes having an ideal temperature to facilitate growth, and typically packaged meats are stored at a temperature much below this to inhibit and delay microbial growth and subsequent spoilage (Montville & Matthews, 2005; Pooni & Mead, 1984; Ray & Bhunia, 2013). Temperature exposure can also influence gene expression in some microbes, resulting in the synthesis of various toxins or lysis enzymes that contribute to meat spoilage and potential health hazards (Montville & Matthews, 2005). Unfortunately, variation in storage temperature is common with the progression of meat through the supply chain (Pooni & Mead, 1984) and therefore, tracking changes in temperature can prove valuable when monitoring spoilage. This function has been the focus of some intelligent packaging innovations.

The Wilson (2012) patent is based on a reactive label that can be placed within a meat package exterior and changes colour dependent on content temperatures. Once a predetermined time/temperature threshold has been met, the label colour change becomes permanent; otherwise it will revert to the original colour once temperature has returned below the threshold. The Arsenault (2012) patent describes a similar device, albeit the label colour change is driven by reactive photonic crystals. A limitation to these approaches is their inability to record and report temperature variations profiles over time, or temperature history. The Chan, Yeung, Chan, & Lee (2013) patent is aimed at correcting this paucity. While this technology also uses reactive photonic crystals that indicate temperature change, these are arranged into crystal units, separated by a hardening polymer, which sequentially and permanently change colour each time a time/temperature threshold is breached. Hence, this label provides a record of temperature history for a packaged meat product. A benefit to using these visual sensors is their relative cost-effectiveness; however this demonstrates that advances in remote temperature sensors are continuing to be made.

The Tang & Liu (2012) patent specifies a remote temperature sensor that continuously relays temperature information from within a package to a central unit. Additionally, this device is operational while microwave sterilised and/or pasteurised, but is relatively cumbersome. In this regard, it is more a quality assurance device rather than a practical inclusion for mass packaged meat products. The Kim, Kim, Kim, Kim, Kwon, Kim, & Cha (2013) patent describes a smaller temperature recording device, that monitors not only temperature and other factors, in real time it also remotely transmits information through a RFID network. This information can also be transmitted directly to a consumer's smart phone and allows information to be available immediately prior to purchase.

5.3.5 Traceability

Almost as a by-product of their targeted and intended function, including those described, sensors have potential applications in product tracking and identification. Communication between sensors and a central unit is two-directional and therefore information can be stored within sensor-based devices located within a meat package. This deposited information could then be used as an electronic tag for identifying product source and storage history (i.e. temperature, pH, gas profile changes) and act as a resource for both consumers and retailers alike. The Babcock & Babcock (2013) patent defines an applicable wireless device that acts to store information shared between sensors and a central unit. The Ramsey & Vaughan (2013) patent describes a similar device, that allows wireless communication and information storage, although with the additional ability to visualise the packaged meat and potential quality information through a 'hook-up' with a smart phone (Figure 14). The Tropper & Batour (2014) patent brings another dimension into traceability, being a personal activity tracking device that detects and records actual movement via an internal gyroscope and accelerometer. This device could be used in meat packaging and provide accurate and rapid information as to the handling of individual meat packages. The application of this device in product recalls or supply chain assessment would be significant.
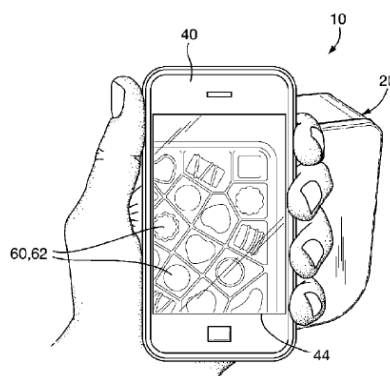

Figure 14. A wireless communication device that allows two-way transmission of information between package and a wireless device (i.e. smart phone) (Ramsey & Vaughan, 2013)

5.4 Active Packaging

5.4.1 Microbial Spoilage Functions

Active packaging has been applied in restricting the microbial spoilage of packaged meat and generally this entails either: 1) Direct insertion of antimicrobial agents into meat packaging; and/or 2) Tailoring hostile packaging conditions for preventing microbial establishment.
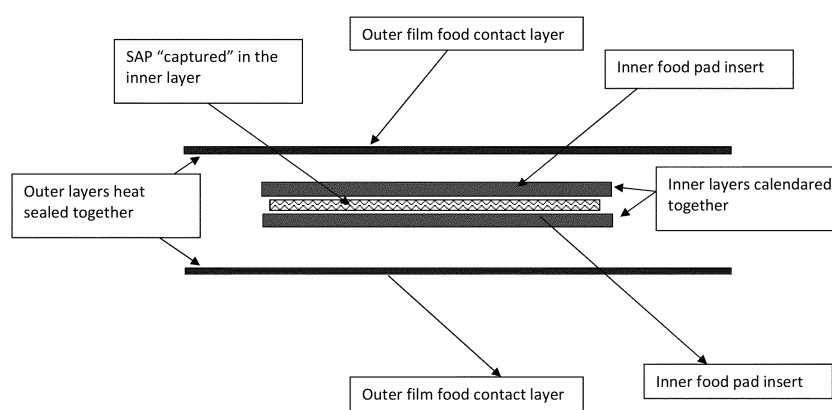
Cross-sectional view of the food pad structure

Figure 15. A biodegradable non-woven polymer absorbance pad with antimicrobial properties for insertion into meat packaging (Durdag, Pendleton, Hamlyn, Gunn, & Etchells, 2013)

The direct approach is used by the Thomas, Dowling, & Katsikogianni (2014) patent, as it applies bioflavonoid coating (i.e. narignin or neohesperidin) to polymeric packaging material. This not only provides antimicrobial functionality, but can improve resistance to oxidative spoilage. The Morris, Bottema, Cullen, Hickey, Knowles, & Pitchford (2013) patent details another meat package surface coating, using ordered nano-arrays of metal or metal oxide nanostructures that inhibit microbial growth. The Dutreux, Hann, & Stark (2014) patent involves the addition of natamycin to a packaged meat environment, potentially via a coating of packaging materials. The natamycin then acts as an antimicrobial agent provided the packaged meat contains sufficient moisture to facilitate this task. Rather than a coating, the Durdag et al. (2013) patent introduces antimicrobial agents to the packaging environment using a package insert (Figure 15). This insert is comprised of a biodegradable polymer, non-woven absorbent pad that contains antimicrobial agents, including silver-based species which have a broad spectrum of strong antimicrobial activity (Quintavalla & Vicini, 2002). A limitation of antimicrobial coating to prevent spoilage is that it only affects meat surfaces with immediate contact to the coated packaging material (Quintavalla & Vicini, 2002). The device described by

Durdag et al. (2013) overcomes this shortfall by also contributing to moisture management within a meat package.

The moisture content within a meat package facilitates microbial growth by creating a suitable environment for proliferation. Therefore, by limiting the presence of 'free water' in a meat package, the potential for microbial spoilage can be lessened (Kerry, 2012). Free water can be measured as a_w and refers to water not bound to meat molecules and is available for biological functions (Dave & Ghaly, 2011; Ray & Bhunia, 2013). As with temperature, spoilage microbes generally require a_w between 0.980-0.950 to support microbial growth, which will cease when an $a_w < 0.900$ is achieved (Beuchat, Komitopoulou, Beckers, Betts, Bourdichon, Fanning, Joosten, & Ter Kuile, 2013; Dave & Ghaly, 2011). Fungal growth can also be limited by low a_w (Duckworth, 1975). These characteristics have resulted in active packaging development to reduce a_w and make packaged meat inhospitable for microbial spoilage. For instance, the Lee, Lee, & Choi (2014) patent uses a moisture absorbent packaging film comprised from a desiccant polyacrylic acid patial sodium salt or attapulgite-synthesised acrylic amide, layered with a polyethylene resin. This affords moisture removal and decreased a_w, however care must be taken in removing moisture from packaged meat, due to the contribution that inherent meat moisture has on eating quality (Aaslyng, Bejerholm, Ertbjerg, Bertram, & Andersen, 2003).

The Cavitt & Faulkner (2012) patent explores another means of inhibiting microbial growth in packaged meat through rendering the thermoplastic polymer resistant to microbial biofilm formation. This alters the surface texture to repel attachment, and in doing so, reduces microbial growth and evidence to perspective consumers when applied to packaging material.

5.4.2 Modified Atmosphere Packaging

MAP can be defined as a method in which gaseous concentrations within an isolated packaging atmosphere are manipulated with a focus on preserving package content quality (Zhou, Xu, & Liu, 2010). For meat packaging, MAP is the focus for much recent innovation in active packaging. The gases of interest to meat packaging inventors are O_2 N_2, CO_2 and carbon monoxide (CO), and the concentration of these are adjusted to manage oxidative and microbial spoilage (Arvanitoyannis & Stratakos, 2012; Eilert, 2005).

The Stubbs (2013) patent uses MAP and actively changes the packaging atmosphere by housing an O_2 emitter, that releases gas at a predetermined rate and is also capable of emitting other gases,. Any gas emitted by this device is generated from chemical reactions or from gas trapped within a matrix. The Machado (2014) patent also releases gas into a package atmosphere, albeit this device relies upon package humidity, but can also release other compounds into the package, such as antimicrobial and/or blooming agents. This complements MAP potential applications in restricting microbial spoilage. For instance, CO_2 is an important inclusion in MAP because of its selective bacteriostatic and fungistatic properties (Kerry, 2012). All these functions stem from the capacity that CO_2 has in changing the cellular membrane functions of microbes, thereby disrupting nutrient

absorption, inhibiting many enzymatic reactions, contributing to intracellular pH shift, and inducing direct morphological protein changes: subsequently affecting physicochemical properties (Ammor et al., 2006; Farber, 1991). It must be noted that many microbes key to meat spoilage are facultative anaerobes (i.e. *B. thermosphacta*), and consequently CO_2 rich MAP is not as restrictive to spoilage as O_2 rich MAP (Ray & Bhunia, 2013). Consequently, MAP must be balanced so as to restrict spoilage microbes without compromising conditions to promote spoilage through another microbial type. Nevertheless, MAP has been reported to improve meat shelf-life by between 50-100% (Kerry, 2012).

A common trend in MAP innovations is that they are based upon single packages rather than multiple or group, which can offer better economies of scale. Yet, some inventors have made efforts towards innovating group MAP. The Bowden, Bowden, & Nagamine (2013) patent describes a method for automatic MAP, in response to a pressurised feedback system, releasing necessary gas or compounds to maintain a predetermined concentration. This method is essentially only practical for group MAP, for example shipping pallets or containers containing many meat products in a shared environment – see Figure 16. The Mir (2014) patent proves to be a complementary design, as it presents meat packaging with numerous micro-perforations to facilitate ventilation of gas build up. These micro-perforations could have another function in allowing group MAP while maintaining individual packaging integrity. However, this design would have its drawbacks in terms of retail usage.
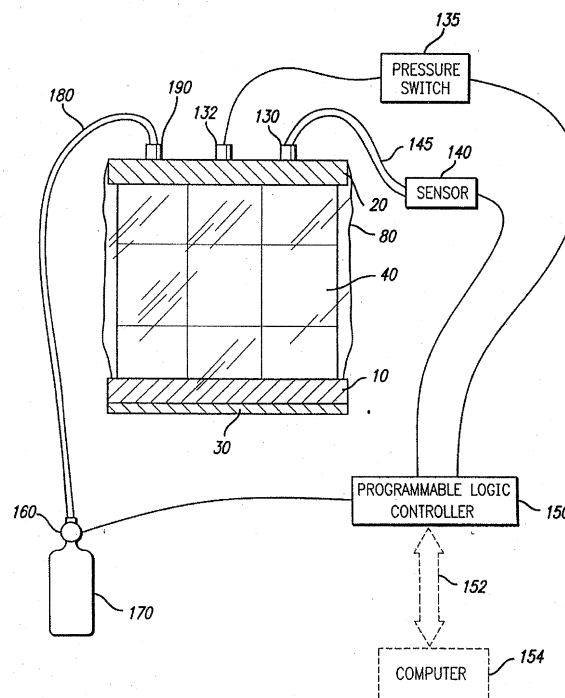

Figure 16. A method for automatically manipulating atmospheric surroundings of multiple packages using a pressurised feedback system (Bowden, et al. 2013)

Lipid oxidation can lead to packaged meat discolouration, rancid odour and flavour development, textural compromise and even the production of some potentially toxic compounds (Morrissey, Sheehy, Galvin, Kerry, & Buckley, 1998). Protein oxidation follows a similar reactive pathway to lipids, that is, both occur from interactions with free O_2 radicals and their oxidative by-products can prompt further oxidation (Baron & Andersen, 2002). The oxidation of protein has significant implications on rancidity and other quality traits for packaged meat. For instance, myoglobin (Mb) is an abundant protein found in meat, and is readily oxidised to cause discolouration. This process has been widely documented (Hopkins, 1996; Khliji, van de Ven, Lamb, Lanza, & Hopkins, 2010; Morrissey, Jacob, & Pluske, 2008). Yet, to provide an overview, with exposure to O_2 Mb is oxidised from the deoxymyoglobin (DMb) configuration to OMb and with prolonged exposure to MMb. Hence, DMb concentrations are greatest during anaerobic storage conditions and this causes fresh meat to have a purplish colour. OMb concentrations increase in the period immediately following exposure to O_2 and prompt the cherry-red meat colouring preferred by consumers. While the transformation of DMb to OMb is reversible, MMb is comparatively permanent and contributes a brown discolouration to meat products (AMSA, 2012; Morrissey et al., 2008). Yet, as MAP generally has a low O_2 concentration this can cause issue when displaying the still packaged meat in regards to matching actual colour to that desired by customers. Overcoming this is the goal of several recent innovations in MAP, generally through the inclusion of Mb blooming agents that initiate the transformation of DMb to OMb.

The Mengel, Latreille, & Siegel (2013) patent aims at promoting blooming of packaged meat via a packaging insert of a porous 'bag' that encapsulates a myoglobin blooming agent that must have contact with the packaged meat to activate. The Siegel & Nelson (2012) patent also promotes blooming with contact, yet instead of an insert, this patent describes a multi-layered packaging film impregnated with Mb blooming agents, ideally at 0.90 mg/in^2. This provides the option to bloom only the meat surface having contact with the film, and limits an extension of blooming into the body of a meat product. The Siegel & Nelson (2014) patent expands upon this previous patent, and impregnates meat packaging film with N_2-containing blooming agents that form nitrous oxide gas during contact with a packaged meat. This latter patent allows blooming on all meat surfaces as it can act to manipulate the package atmosphere as a means for MAP. These patents also have to capacity to introduce antioxidants to a packaging environment and reduce spoilage associated with lipid and protein oxidation. However, as apparent, not all oxidative reactions negate meat quality. For instance, myofibril oxidation can act to improve meat tenderness through its weakening of myosin cross-linkages and myofibrillar structure (Lund, Heinonen, Baron, & Estévez, 2011). Hence, any manipulation of packaged meat oxidative potential must be carefully balanced.

5.5 Packaging Integrity

Meat packaging acts to provide a physical barrier against external contamination and spoilage agents introduced either by accident or intentionally. This function assures product quality and safety, yet is insufficient to match current demands for the

maintenance of integrity characteristics, while addressing marketability, value-adding potential and environmental considerations. This has also been an area of recent innovation.

The Siddiqui (2014) patent presents a multi-layered packaging film comprised of an outer polyethylene layer surrounding inner layers of polyamide and PVA. This contributes to a durable and effective barrier against moisture and air permeation, while optimising the optical properties of the film and allowing an uninterrupted view of the packaged meat. A possible interference to viewing a packaged meat arises from moisture causing a fog build-up that ghosts or obscures clear visualisation. The Montcrieff & Siu (2013) patent offers a counter to this effect, being a peelable anti-fog meat packaging film that is immune to condensation formation and associated visual impairments. This film can also have ink or metalized layers included to allow decoration of the packaging to be readily altered, thus improving market appeal. The Tilton (2014) patent shares the same objective of improving market appeal of retail food packs. It describes the combination of a pliable and durable packaging film with the capacity to serve as a printing surface. These traits are facilitated with the inclusion of one or more mineral layers within the film matrix, providing a bright white printing surface that readily accepts ink.

Biodegradable or multifunctional meat packaging provides a means to reduce waste and promote environmental well-being, in-line with retailer and consumer pressure. Therefore, this has been the focus of recent meat packaging innovations. For instance, the patent by Lee (2014) describes a biodegradable plastic made from polyethylene and polycaprolactam that acts as a non-toxic, tasteless, and odourless packaging option that readily breaks down when discarded. The aforementioned Tilton (2014) patented film is also a biodegradable option, as a consequence of its high mineral content that is included as film layers using cross lamination. The Xiaojing, Jian, Fei, & Xianona (2013) patent, while biodegradable, employs another approach to improving environmental impacts. This packaging film is edible, and prepared using a lactalbumin solution that is combined with a natural anthocyanin extract and plasticiser. Furthermore, this edible packaging film can potentially have reactive ink incorporated that allows the film to sense pH changes in packaged meats which is then reflected in film colour shifts. The Mulyono (2014) patent envisions another edible packaging bioplastic manufactured from seaweed and fortified with vitamins, minerals, food additives or other ingredients. This permits cheap and environmentally-friendly packaging. But, the use of the majority of currently available edible/biodegradable packaging materials for direct application to meat products, especially fresh meat products, is limited as most have the propensity to absorb moisture over time, thereby disrupting the physical packaging structure of the material. However, they do provide an innovative means of overcoming; wastage issues through their capacity to reduce packaging waste by being cleverly combined with more light-weighted conventional packaging materials in realistic industrial applications which require product quality maintenance for longer periods of time, layer migration or layer separation in meat-based products which have parallel lines of layered manufacture and nutritionally poorer meat products.

5.6 Complementary Studies

At present there is extensive information regarding smart packaging of meat products. This knowledge, however, predominantly exists within theoretical scientific literature that explores individual facets of smart packaging or its underlying principles. For instance, meat spoilage agents and efforts towards their limitation is the topic of several reviews (Coma, 2008; Dave & Ghaly, 2011; Kerry et al., 2006). Likewise, intelligent sensors and quality indicators (Kuswandi et al. 2011; Pereira de Abreu et al. 2012a), health and safety implications on meat packaging (Dainelli, Gontard, Spyropoulos, Zondervan-van den Beuken, & Tobback, 2008), and summations of future applications and the potential of smart packaging (Kerry et al. 2006; Restuccia, Spizzirri, Parisi, Cirillo, Curcio, Iemma, Puoci, Vinci, & Picci, 2010) have also been meticulously reviewed. Obvious in these reviews there is support for the core fundamentals that instil the functionality to the innovations and patents discussed in this paper. Consequently, they provide much to the scientific verification necessary to support recent and future enhancement in smart meat packaging technologies.

6.0 Innovations in Meat Packaging Technology Workshop

This project facilitated the 'Innovations in Meat Packaging Technology Workshop' from AMPC Events which occurred on April 23rd 2015 at the Novotel Brisbane Airport (Brisbane, Queensland: Australia). This was designed for red meat processing industry personnel (including innovation managers, sales and marketing managers, quality assurance managers and plant/production managers) to provide an opportunity to discuss current and future meat packaging trends with leading packaging and meat science experts – specifically the authors of this report.

This workshop provided attendees with a better understanding of recent developments in meat packaging and future innovations which have application in the red meat processing industry (free of charge) via four presentations:

1. **Workshop Introduction** (Dr David Hopkins): This presentation defined the workshop basis with reference to the scope of packaging technology and application within a global context and introduced key personnel, the sequence of presentations and allowed stakeholders the opportunity to introduce themselves/organisations.

2. **Application of Smart Packaging Technologies for Muscle-based Food Products** (Dr Joe Kerry): This presentation defined smart packaging and categorised technologies and approaches into three distinct groupings (Active, Intelligent, Consumer Interfacing Technologies) where upon examples currently employed were discussed with regards to their scientific basis and actual outcomes and effects on product qualities and consumer acceptability.

3. **Smart Packaging Patents** (Dr Benjamin Holman): This presentation provided insight into recent (since 2012) patents that describe technologies with application to smart packaging. Also discussed were the necessary steps required to advance from invention to adoption (i.e. validation, education, etc).

4. **Development, Application and Potential Future for Smart Packaging: Outlooks and Opportunities** (Dr Joe Kerry): This presentation outlined the challenges which smart packaging must address and sponsored future widespread adoption of smart packaging. It also emphasised that smart packaging was 'not the silver bullet' and other packaging options should be explored for the holistic improvement of packaging – this was validated by explored case studies.

6.1 Outcomes

This workshop was well attended (approximately 20 stakeholders in attendance) and was chaired by an AMPC representative (John McGuren).

Throughout the workshop many questions were posed and answered (both with reference to stakeholders' specific organisations and the industry as a whole. These queries/statements included (but were not limited to):

- What are retailers/consumers responses to smart packaging?

- Smart packaging technology should not be pushed down from the processors end, rather it should consumer driven.

- Should the indication of freshness be reliant on a single sensor?

- What implications are there from the consumer interpretations of freshness?

- What environmental concerns (i.e. plastic waste) can smart packaging overcome?

- Can packaging improve product integrity and quality opposed to solely shelf-life preservation?

- Is there a local contact to discuss smart packaging technologies with? What technologies can we apply now?

In addition to the discussion, attending stakeholders also requested a copy of each presentation.

Figure 17. Dr Joe Kerry presenting at the innovations in smart packaging workshop.

7.0 Achievement of Objectives

The report demonstrates the successful completion of the original project objective – to outline current and future trends in meat packaging technologies, with a focus on smart packaging advances in product quality preservation and monitoring, by reviewing available scientific literature and relevant national/international patents.

8.0 Concluding Remarks

8.1 Review of Literature Conclusions

The ultimate incentive for deployment of any new technology is cost. The cost effectiveness of smart packaging devices is dependent on the perceived benefits derived from such systems. Processors must ultimately derive benefit from increased profit margins and consumers must derive benefit as 'utility' or satisfaction from economic exchange. Economies of scale suggest that the cost of many active packaging devices (e.g. scavengers, absorbers, emitters) or intelligent packaging devices such as O_2 sensors, TTIs or passive RFID tags are not currently or will not be a factor prohibitive to mass commercialisation. What little consumer-attitude information that is available seems to be positive towards such packaging concepts (Lahteenmaki & Arvola, 2003).

Changes in consumer preferences have led to innovations, developments and patents being held for new packaging technologies. Smart packaging which is active in nature is useful for extending the shelf life of fresh, cooked and other meat, poultry and seafood products. Forms of active packaging relevant to muscle foods include; O_2 scavengers, CO_2 scavengers and emitters, moisture absorption, antimicrobial packaging, antioxidant packaging and odour or flavour removal. Recognition of the benefits of active packaging technologies by the food industry, development of economically viable packaging systems and increased consumer acceptance opens new frontiers for active packaging technology. Commercially, there is already widespread use of O_2 scavengers in both fresh and pre-packed cooked sliced meat products. Antimicrobial packaging is gaining interest from researchers and industry due to its potential for providing quality and safety benefits, especially in the area of nanotechnology – using nanoparticles and other related materials. Future research in the area of microbial active packaging should focus on naturally-derived antimicrobial agents, bio-preservatives and biodegradable packaging technologies. The possibility of utilising additional active packaging technologies, as currently applied to other foodstuffs, for safe and effective storage of meat, poultry and seafood also merits investigation.

In order to address the present imbalance between potential and actualisation of intelligent packaging application, a number of research paucities need to be filled and already available technologies/patents validated. These include further modelling of the interactions between foods and microbes and their metabolites under dynamic storage conditions, better understanding of correlations between spoilage indicators and sensory quality, effective incorporation of sensors and indicators into high-volume packaging

processes, knowledge on the behaviour of intelligent packaging devices at all points of the storage and distribution chain, issues relating to sensitivity (including over-sensitivity) and reliability. Food manufacturers can ill-afford inaccurate extrapolations based on a limited knowledge base. Nor will they risk commercial investment on unproven technologies.

The potential advantages of smart packaging which is intelligent in nature for muscle-based foods are many and varied. Apart from aspects of quality, safety, and distribution already outlined, intelligent packaging offers considerable potential as a marketing tool and the establishment of brand differentiation for meat products. Assuming intelligent packaging can effectively provide solutions to current processor and consumer problems, it appears likely that intelligent packaging systems for muscle-based food products will become more commercially viable and common-place in the years to come.

8.2 Review of Patents Conclusions

Meat packaging is a dynamic product that continues to evolve to match its changing role as defined by consumer and retailer specifications. The scope of this role shift is evident by the diverse number of recent innovations in smart packaging, summarised in the fields of active and intelligent packaging, and packaging integrity within this paper. However, following this review of recent patents a number of concerns were identified that could hinder widespread adoption of these, for the most part, beneficial smart packaging technologies.

The expense involved with producing, monitoring and including many recent patents for advancing smart packaging is a formidable hurdle to their adoption. These stem from these devices being at the 'cutting edge' of technology and hence, are relatively complex and labour intensive to produce. Furthermore, intrinsic to meat packaging is their disposability – with consumers typically discarding all packaging material following usage opposed to returning for reuse or recycling. Consequently, ideal meat packaging must be cheap to produce otherwise the disposal of smart packaging components would result in significant increases in price. Additionally, and especially with intelligent packaging, the extra infrastructure necessary to monitor and amalgamate sensor data to provide insight into meat quality and freshness would be a heavy monetary burden for any meat packaging organisation. Even if a meat company found a mechanism to address the factors presented to this point, the company in question would be at the mercy of regulatory authorities to approve the use of such technologies, and legislation pertaining to the use of smart packaging materials can be extremely restrictive in some regions of the world.

Another limitation to recent smart packaging adoption is their apparent singularity of purpose. For instance, the majority of devices reviewed are described in terms of an isolated action rather than their potential inclusion in a conglomerate of smart packaging with the shared goal of 'ideal meat packaging'. Admittedly, this does permit individual tailoring of meat packaging, however without the benefit of educated decision making. In fact, the requirement for smart packaging technologies to communicate individually with

each consumer is questionable and the scale and directed focus of application of such technologies needs to be carefully considered in the future. Most smart packaging technologies underpin or support quality assurance systems throughout the distribution chain from manufacturer to retailer, consequently this arguably should be the focus for implementation of smart packaging technologies. This highlights the final significant limitation to adoption – scientific verification. As true with all novel and emerging technologies, often the invention outpaces scientific assessment which can cast doubt on the merit and/or the extent of the effect of the smart packaging. This lag period can contribute to stagnated adoption.

There are factors promoting the adoption of recent innovations in smart packaging. For instance, technological advancements are moving forward exponentially in many complementary areas to smart packaging, such as nanotechnology, electrical engineering, and biochemistry. This could assist in alleviating monetary limitations and improve the duality or multi-functionality of these reviewed patents. Also, increased consumer knowledge on product quality can support the preferential purchase of smart packaged meats and willingness to pay a premium for the reassurance of quality. The continued support for independent scientific verification of recent patents will add a guarantee to device capacity. Therefore, it can be concluded that many of these reviewed recent patents constitute a feasible option for widespread adoption for meat packaging, although with a provision that effort is made to better match device purpose to achieving the objectives outlined for ideal meat packaging.

8.3 Advice for Investment (Research)

Several key observations were made during these reviews which should be considered when formulating the direction of investment into smart packaging research:

- Often significant improvements to muscle-based food products are achieved using holistic changes to production, processing and packaging systems rather than introducing smart packaging technology into the existing system.

- Adoption of smart packaging should be consumer driven, with best results for all stakeholders expected from more communication and cooperation between processors and retailers (the latter being essential members of any discussion forum).

- Legislative (i.e. packaging insert/coating restrictions and safety concerns), environmental (i.e. recyclability), and system usage (i.e. application, economic) considerations must be made before adopting any smart packaging option.

- Validation of existing smart packaging technologies and patents is needed – and this will promote adoption and further innovation that may contribute to more cost-effectiveness. For example a lack of systematic and comparative data exists on the behaviour of O_2 sensors over wide temperature ranges and there is considerable potential for the development of freshness indicators based on established knowledge of quality indicating metabolites.

- Clarification of information availability (whether solely for retailers/processors, or consumers) must be established with consideration of all stakeholders. This should consider consumer pack interactive aspects, whereby consumers must be educated to make conscious decisions as to whether or not to access smart packaging information (passive and discrete smart packaging versus participatory packaging).

- The potential for smart packaging technologies to be applied as a combination. For instance, twinning active packaging systems with intelligent packaging systems could facilitate better control over a packaged environment/product.

- Seldom would intelligent packaging be required in every package, instead including several intelligent packaging technologies distributed with traditional packaging could provide insight to population status.

8.4 Project Output

In addition to this report, the two reviews (review of literature and review of patents) are to be submitted for individual publication in peer-reviewed scientific journals.

The workshop also provided the opportunity for meat packaging stakeholders to have 'face-to-face' discourse with the experts compiling these reports and provide tailored responses to their individual concerns. It also established an important dialogue between researchers, AMPC and industry which demonstrates promise when considering future investment into smart meat packaging technologies.

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