Meat and fish packaging and its impact on the shelf life – a review

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Received July 29, 2022
Accepted December 13, 2022

Abstract

The shelf life of fresh meat and fish is highly dependent on packaging technologies. The aim of any packaging system for fresh flesh foods is to prevent or delay undesirable changes to the appearance, flavour, odour, and texture. Moreover, microbial contamination, together with lipid and protein oxidation, are major concerns for meat and products thereof in terms of food safety. Modified atmosphere packaging (MAP) is widely applied in the packaging of both meat and fish. This packaging technology extends shelf life and improves appearance; however, several variables must be considered, such as temperature control and differences in gas compositions in combination with different types of meat. This review provides an overview of the available information on packaging technologies, from the perspectives of their characteristics, application types, and effects on the shelf life of poultry, meat, and fish. Special attention is paid to the MAP and active packaging.

Modified atmosphere packaging, freshness, microbiological quality

Food packaging is one of the most important processes in the food industry, as it is crucial in maintaining the quality of food products during storage, transportation, and distribution. The primary function of packaging has been classified into four categories: containment, protection, communication and convenience. In other words, packaging is intended to 1) contain the food, 2) protect it from external influences such as biological, chemical or mechanical damage, 3) communicate to the consumer as a marketing tool and 4) to provide consumers with ease of use, nutritional information, and convenience (McMillin 2008; Lee et al. 2015; Sarkar and Kuna 2020).

Modern society has extensively investigated the replacement of traditional food packaging systems with new ones. These packaging systems are an effective way to extend or maintain shelf life and preserve quality for a range of fresh products such as vegetables, fruits, meat and fish. Many packaging systems currently exist; each with different attributes and applications. These systems range from overwrap packaging for short-term chilled storage and/or retail display, to a variety of specific active or intelligent packaging systems (Ščetar et al. 2010; Lee et al. 2015).

Food products of animal origin are a diverse group of foods with specific demands for storage and, hence, for packaging. Some of these, such as raw meat, ham, fresh milk or fresh cheese are intended for rapid consumption whereas others, such as dry fermented sausages or some types of cheese, are suitable for long-term storage. According to the so-called Hurdle Effect Theory, the conditions of food storage (external temperature, relative air humidity, composition of the packaging atmosphere, duration of storage) constitute the external factors. These, together with the internal factors (food composition, water activity a_w, pH, redox potential and texture) represent the principal factors influencing shelf life and safety (Leistner 2000). Safety is a major concern for all foods of animal origin, as these

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provide a suitable environment for many microorganisms, including pathogenic ones, and are a common source of food-borne diseases. Extending shelf-life of such foods while maintaining safety as well as the sensory and nutritional values is a major challenge.

Modified atmosphere packaging

Modification of packaging atmosphere is widely used as an effective technology which can significantly extend shelf life and improve quality level of most food products. The phrase 'packaged in a protective atmosphere' must be stated on the packaging of the foods whose shelf life has been extended by means of packaging gases. Only gases authorised pursuant to Regulation (EC) No 1333/2008 can be used for this purpose (Regulation (EU) No 1169/2011).

Modification of the internal packaging atmosphere may take place at the level of total pressure (vacuum packaging) and/or partial pressures of gas components; the composition of the gas mixture inside the packaging can, therefore, be much different from that of normal atmosphere under the condition that total pressure is in equilibrium with the outside atmosphere. This case is called modified atmosphere packaging (MAP). The MAP condition can be achieved actively (initial substitution of normal air with a selected atmosphere) or passively (change of the internal atmosphere from the natural consequence of the balance between gas permeation across the package walls and gas production/ consumption inside the package). For completeness, classification of the possible ways for changing the package internal atmosphere should also include the active packaging, i.e., possible gas scavenging as well as possible gas releasing (Lee et al. 2015). Modified atmosphere packaging is used to slow down the respiration rate of a product, to reduce enzymatic reactions, and to inhibit microbial growth in order to extend shelf life and satisfy the needs for packaged food quality (Chen et al. 2003).

Gases inhibit microorganisms by two mechanisms. First, they can have a direct toxic effect that can inhibit growth and proliferation. Carbon dioxide, ozone, and oxygen are directly toxic to certain microorganisms. The second, indirect, mechanism lies in altering the competitive environment as a consequence of altering the atmosphere. An example of this indirect antimicrobial activity is the replacement of oxygen with nitrogen. The anoxic atmosphere created by the use of N_2 or other inert gas will select for anaerobic, aerotolerant lactobacilli acidifying the environment and thus creating another obstacle for pathogenic microorganisms (Thippereddi and Phebus 2007).

Gases in MAP

The air normally contains 78.08% nitrogen, 20.96% oxygen, and 0.03% carbon dioxide (Lavieri and Williams 2014). The same gases are, at the same time, the ones most widely employed in MAP but they are used in different proportions and combinations ensuring the balancing of safe shelf life extension with optimal food characteristics. A few other gases have also been used, including helium, nitrous oxide, ozone, neon, argon, chlorine, or carbon monoxide, but their use is rather experimental (McMillin 2008; Lavieri and Williams 2014).

Most O_2 reactions in food (oxidation reactions) cause food quality degradation. To name but a few, we can mention fat oxidation, browning reactions, and pigment oxidation. Oxygen also promotes the growth of most spoilage microorganisms. Therefore, O_2 is usually excluded from the packaging atmosphere to improve the quality of preservation (Lee et al. 2008; Lee et al. 2015). In contrast, high-O_2 MAP plays an important role in maintaining meat colour through maintaining the muscle pigment myoglobin in its oxygenated form, oxymyoglobin. Low oxygen concentrations lead to the oxidation of oxymyoglobin to metmyoglobin and meat loses its red colour. In order to minimise metmyoglobin formation in fresh red meat, oxygen must be either excluded from the packaging environment to below 0.05% or present at saturating levels (80–90%) (Ščetar et al. 2010).

Carbon dioxide (CO_2) in MAP acts through the inhibition of bacterial and fungal growth. It extends the lag phase growth and reduces the rate of logarithmic growth, thus enhancing the shelf life of perishable foods (Ščetar et al. 2010; Lee et al. 2015). CO_2 is a colourless, odourless, and non-combustible gas highly soluble in water and fat at lower temperatures. Dissolved CO_2 can cause acidification of food surfaces during storage, which helps to suppress the growth of many spoilage microorganisms. The solubility of CO_2 in aqueous foods increases with moisture increase and temperature decrease (Sivertsvik et al. 2002; Lee et al. 2008; Lee et al. 2015).

A drop in surface pH is observed in MAP products because of the acidic effect of dissolved CO_2, but this could not entirely explain all of the CO_2 bacteriostatic effects. The effect of CO_2 on bacterial growth is complex; four mechanisms of CO_2 action on microorganisms have been identified: 1) alteration of cell membrane function including the effect on nutrient uptake and absorption; 2) direct inhibition of enzymes or reduction in the rate of enzymatic reactions; 3) penetration of bacterial membranes, leading to intracellular pH changes; 4) direct changes in the physico-chemical properties of proteins (Sivertsvik et al. 2002).

On the other hand, a modified atmosphere with very high CO_2 concentration may sometimes induce some deleterious effects in high moisture foods such as fresh fish and meats. High dissolution of flushed CO_2 gas in the foods reduces the headspace volume in case of semi-rigid plastic package resulting in package collapse. Moreover, solubilized CO_2 causes acidification on the surface and therefore a change of sensory properties (Lee et al. 2008) (Table 1).

Table 1. Pros and cons of the use of modified atmosphere packaging in packaged meat and fish.

	Advantages	Disadvantages	Application
High-O_2 atmosphere (> 80%)	Formation of a thick layer of oxymyoglobin → improving meat colour; controlling anaerobic bacteria	Aerobic bacterial growth; lipid and protein oxidation	Red meat
Low-O_2 atmosphere (< 2%)	Slowing down the lipid oxidation; suppression of aerobic bacterial growth	Possible oxidation of oxymyoglobin to metmyoglobin → meat colour deterioration (O_2 levels of 0.15–2.0% predispose red meat to browning)	Fish
Vacuum packaging	Formation of deoxymyoglobin → purple colour; suppression of aerobic bacterial growth; slowing down the lipid oxidation	Exudate held in wrinkles may be more susceptible to bacterial growth	Red meat, poultry, fish
High-CO_2 atmosphere (≥ 20%)	Inhibition of bacterial and fungal growth; solubilized CO_2 causes acidification on → helps to suppress bacterial growth conditions	Possible package collapse (CO_2 > 80%); possible formation of metmyoglobin; solubilized CO_2 causes acidification on the surface → change of sensory properties	Red meat (20%), poultry(20–75%), fish (20–75%)

Nitrogen is used as an inert filler gas either to reduce the proportions of the other gases or to prevent packaging collapse. Displacement of oxygen by nitrogen acts to block out the oxidative chemical and physiological reactions, preserving the food quality (Lee et al. 2008; Ščetar et al. 2010).

Vacuum and vacuum skin packaging

Another way of the modification of the internal packaging atmosphere is vacuum packing (VP). It involves removal of air from within the pack and maintaining an oxygen-deficient environment around the product by sealing the product in a flexible film of low oxygen permeability. This technique is used for improving the shelf life of primal and subprimal meat cuts, boneless meat, and also for processed meat products such as sausages, patties, nuggets, etc.

One of the disadvantages of VP is the exudates (purge loss) formed after air removal. Vacuum skin packaging (VSP) is an advanced type of vacuum packaging which helps to avoid the formation of film wrinkles. This method involves placing the product on a tray and wrapping it in a film under a vacuum at an elevated temperature. The heat causes the softening of the top film which then tightly covers the product, hence the designation of "skin". The result is a decrease in purge loss and a longer shelf life in comparison to conventional vacuum packaging (Kameník et al. 2014; Lopacka et al. 2016).

Active packaging

Active packaging is defined as the incorporation of certain compounds into the packaging system to extend shelf life and maintain or enhance food quality (Lee et al. 2015). This type of packaging is used as a substitute for conventional food processing techniques like high heat treatments, dehydration, brining, acidification, and addition of preservatives.

Based on the European Union Guidance to the Commission Regulation (EUGCR) No. 450/2009, active packaging is a type of food packaging with an extra function in addition to that of providing a protective barrier against external influence. The packaging either absorbs food-derived chemicals from the food or from the environment within the packaging surrounding the food or releases substances such as preservatives, antioxidants, and flavourings into the food or the environment surrounding the food (EU 2009).

The nature of active agents that can be used is very diverse. Active packaging applications for use within the food industry use additives that have the potential of scavenging oxygen, adsorbing/generating carbon dioxide, moisture, ethylene, flavour or odour, releasing antioxidants, preservatives, ethanol, sorbates, and/or maintain temperature. Another type of active packaging, antimicrobial packaging, has been used to delay spoilage and improve the safety of food materials by incorporating antimicrobial agents into packaging films to suppress the activities of targeted microorganisms. Active packaging often complements the MAP functions (Lee et al. 2015; Sarkar and Kuna 2020).

Oxygen-scavenging packaging

Vacuum packaging or MAP can reduce the residual oxygen level in the headspace down only to 0.5–2vol% which may be insufficient for some types of food. Oxygen scavengers may reduce the oxygen level to less than 0.1vol% (Gibis and Rieblinger 2011; Dey 2019), therefore, O_2-scavenging technology may be used appropriately to remove residual O_2 after MAP or vacuum packaging. Moreover, this technology can also absorb the O_2 permeating through the packaging film. O_2 absorbers applied to meat product packaging can prevent the growth of moulds, aerobic bacteria such as *Pseudomonas* and oxidative damage to flavours and muscle pigments, thus preventing discoloration (Coma 2008).

Existing O_2 scavenging technologies are based on the oxidation of one or more of the following substances: iron powder, ferrous carbonate, ferrous oxide, ascorbic acid, photo-sensitive dyes, catechol, enzymes (such as glucose oxidase and ethanol oxidase), unsaturated fatty acids (such as oleic, linoleic, and linolenic acids), or immobilized yeast on a solid substrate (Dey 2019; Sarkar and Kuna 2020). Currently available oxygen-absorbing systems can be divided into the insert type (sachets, self-adhesive labels, and adhesive devices) which are placed in the package and the reactive polymer structure type which covers monolayer and multilayer materials and closure liners for bottles (Lee et al. 2008).

The majority of used oxygen scavengers are iron-based. The basic oxidation reaction by which iron absorbs oxygen can be described as:

$4\ Fe + 3\ O_2 + 6\ H_2O \rightarrow 4\ Fe(OH)_3$

The oxidation of iron requires water, the moisture usually being present as a vapor from the moist food or, for dry products, added to the absorbent during packaging. After a reaction with water, a reactive hydrated metallic reducing agent that scavenges oxygen and converts this agent into stable oxide is created (Lee et al. 2008; Lee et al. 2015).

Carbon dioxide emitting/absorbing packaging

Depending on the type of packaged food, CO_2 emitters or absorbers can be used, most often in a sachet or label form. CO_2 emitters are frequently used in MAP systems for meat in order to balance out CO_2 losses due to dissolution into the meat and permeation through the packaging material. CO_2 dissolution from CO_2-enriched headspace into the flesh foods in the MAP products can cause partial vacuum or collapse of semi-rigid plastic trays. In such cases, the production of CO_2 amounting to the missing amount of gases can help maintain package integrity and appearance (Coma 2008; Lee et al. 2008; Fang et al. 2017).

Carbon dioxide absorbers consisting of either calcium hydroxide with sodium hydroxide or potassium hydroxide, calcium oxide, and silica gel may be used to remove excess carbon dioxide during storage in order to prevent the package from bursting. They are often used for dehydrated poultry products and beef jerky (Fang et al. 2017).

Antimicrobial active packaging

Because food spoilage usually begins on food surfaces due to the presence and growth of pathogenic or spoilage microorganisms, the incorporation of antimicrobial agents into packaging materials is used to suppress the activities of targeted microorganisms (Lee et al. 2008). Antimicrobial substances can be incorporated into a sachet or pad inside the package (Otoni et al. 2016) or directly incorporated into the packaging film (Sung et al. 2013). The packaging also can be coated with a matrix that acts as a carrier for antimicrobial agents, or inherently antimicrobial polymers (e.g. chitosan) (Fang et al. 2017).

The antimicrobial agents used include silver ions, ethanol, chlorine dioxide, organic acids, bacteriocins, chitosan, chelating agents, inorganic acids and enzymes such as lysozyme (Lee et al. 2008; Lee et al. 2015). The use of artificial active packaging additives is being increasingly replaced by the use of natural ones. Natural extracts obtained from plants, herbs, and spices are generally recognized as safe to be used and have been studied as antimicrobials to extend the shelf life of packed food of animal origin (Mytle et al. 2006; Mahgoub et al. 2019). The principle of antimicrobial packaging function is the controlled migration of antimicrobial agents from the packaging material to the food surface, which can be achieved by direct contact between the food and packaging material or through the gas phase diffusion from the packaging layer to the food surface (Lee et al. 2008).

Meat and poultry packaged in MAP

Among the packaging technologies developed by and for meat and meat products, MAP has led to the development of fresh and minimally processed food preservation (Coma 2008). The efficacy of MAP in prolonging the shelf life of packaged meat relies on the antimicrobial properties of CO_2 present inside the package (Arvanitoyannis and Stratakos 2012).

The use of CO_2 for inhibiting bacterial growth is not a new technology. In 1877, Pasteur and Joubert observed that *Bacillus anthracis* can be killed by CO_2 and five years later, the first article on the preservative effect of carbon dioxide on food was published, showing the extended storage life for meat placed inside a cylinder filled with a carbon dioxide atmosphere (Sivertsvik et al. 2002).

Despite the high antimicrobial effect of CO_2, its amount in the MAP of meat and fish is limited. High CO_2 dissolution may cause not only package collapse as mentioned earlier, but also an increased drip or exudates of flesh foods. Low pH resulting from dissolved CO_2 may cause discolouration on the surface and taste change of fresh muscle foods. Usually 20–60% CO_2 levels are required for effectiveness against aerobic spoilage bacteria by penetrating membranes and lowering intracellular pH (McMillin 2008; Lee et al. 2008).

Being lowly soluble in water, N_2 has minimal effects on metabolic reactions in the meat and lipids and has little antimicrobial activity on its own. In any case, nitrogen is used for filling up of protective atmosphere to the right level of gas content. High-oxygen MAP is the packaging method of choice for fresh meat in western Europe as it prolongs the shelf life of meat by reducing microbial growth and preserving red meat colour compared to traditional aerobic packaging (Li et al. 2012; Jongberg et al. 2014). However, high concentrations of oxygen and prolonged storage times accelerate the oxidative processes (McMillin 2008; Jongberg et al. 2014).

Typically, fresh red meats are stored in a modified atmosphere containing 80% O_2 : 20% CO_2 because fresh meat is very sensitive to discolouration caused by low levels of oxygen. Low partial oxygen pressure values will lead to the development of brown colour due to the conversion of myoglobin to metmyoglobin (Lund et al. 2007; Arvanitoyannis and Stratakos 2012). Fresh meat colour is one of the most important aspects of quality that determines the consumers' purchase choice. Meat discolouration is perceived by consumers as an indicator of a lack of freshness and wholesomeness (Li et al. 2012). A high oxygen content in MAP gives beef a stable bright-red colour due to the formation of a thick layer of oxymyoglobin at the meat surface that masks the underlying metmyoglobin presence (Li et al. 2012). However, some studies have found that high oxygen MAP negatively affects meat quality (Lund et al. 2007; Lagerstedt et al. 2011; Arvanitoyannis and Stratakos 2012). An increased level of oxygen can induce lipid oxidation, thereby causing rancid off-flavours. High levels of oxygen can also cause intermolecular cross-linking, which subsequently decreases the tenderness and juiciness of the meat and as well as its nutritional value, which is associated with the loss of essential amino acids and reduced digestibility (Lund et al. 2011). Abdullah and Buchtová (2020) compared the effect of high oxygen MAP (80% O_2 : 20% CO_2) and MAP without oxygen (70% N_2 : 30% CO_2) on freshness indices of chicken skin and wings and found that high oxygen MAP only had a positive effect on skin colour, whereas MAP without oxygen may be preferable for extending shelf life.

Vacuum packaging sets anaerobic conditions for the meat, which leads to further shelf life extension and provides a stable colour. Vacuum reduces atmospheric oxygen which is otherwise in contact with the meat surface, and bright red oxymyoglobin changes to purple deoxymyoglobin as a consequence. However, purple meat colour is not considered as attractive as bright red. Moreover, vacuum promotes the release of meat juices that accumulate in the surface folds created by the wrapping film. Both of these characteristics have caused a decrease in the share of vacuum packed meat in retail shops (Kameník et al. 2014; Lopacka et al. 2016).

Vacuum skin packaging minimizes the formation of wrinkles and air pockets by heating the upper cover film and making it shrink tightly around the meat. Meat in such packages has a longer shelf life and slower bacterial growth compared to VP (Li et al. 2012; Kameník et al. 2014). Li et al. (2012) compared the effects of VSP, VP, and MAP (20% CO_2 : 80% O_2) on the colour of beef. The colour of samples packed in VSP and MAP was similar after 5 days of storage, better than VP samples. Pros and cons of the use of MAP in packaged meat and fish are shown in Table 1.

Meat and poultry packaged with oxygen scavengers

Levels of oxygen in meat packaging similar to those found in air influence not only the change in colour but can also facilitate microbial growth, lipid oxidation, development of off-flavours and off-odours and nutritional losses. Oxygen-scavenging packaging, controlling the level of oxygen to which the product is exposed, is another means of improving product quality and extending the shelf-life of meat and meat products (Fang et al. 2017).

The body of scientific literature contains many studies, which examine the influence of oxygen scavenger sachets on fresh beef discolouration (Kerry et al. 2006; Ščetar et al. 2010). Usually, a combination of oxygen scavengers and MAP without oxygen is utilized to set anaerobic conditions and deoxymyoglobin formation. Tewary et al. (2001) examined the effect of two commercial oxygen scavengers (Ageless® FX-100 and FreshPax® R-2000), in combination with controlled atmosphere packaging, on the discolouration of M. psoas major in packs filled with nitrogen and stored at 1 ± 0.5 °C. Steaks packed without oxygen scavengers showed greater discolouration and contained significantly more metmyoglobin compared to steaks packed with oxygen scavengers. The prevention of metmyoglobin formation was influenced by the number but not by the type of oxygen scavenger employed. Other authors reported that discolouration could be prevented in ground beef if large numbers of scavengers were used in each pack to bring residual oxygen to < 10 ppm within 2 h of packaging (Ščetar et al. 2010).

Martinez et al. (2006) reported that fresh pork sausages stored without oxygen either in a vacuum or in a modified atmosphere (20% CO_2 : 80% N_2) with an oxygen scavenger had reduced psychrotrophic aerobe counts and extended shelf-life in terms of colour and lipid stability compared to an oxygen-containing modified atmosphere (20, 40, 60 and 80% O_2). Comparing the results of the samples stored in MAP (20% CO_2 : 80% N_2) with and without oxygen scavenger, a difference in the colour stability was noted in favour of samples with MAP and oxygen scavenger.

The effects of MAP (70% CO_2 : 30% N_2) and iron-based oxygen scavengers with various absorption capacities (Ageless ss100, ss300, and ss500) on microbiological and oxidative changes in chicken thigh meats were evaluated by Demirhan and Candogan (2017). The results of their study suggested that MAP suppressed microbiological growth and retarded lipid and protein oxidation in chicken thigh meats, with a 9-day shelf life extension with non-significant effects of oxygen scavengers. Similarly, Jongberg et al. (2014) proved that MAP (80% CO_2 : 20% N_2) with or without oxygen scavenger extended the microbiological shelf life of chicken thigh meats by approximately 9 days, and oxygen scavenger application did not result in an additional shelf-life extension to MAP.

Antimicrobial packaging of meat and poultry

Antimicrobial packaging is an important concept in the active packaging of meat. A large number of antimicrobial agents have been tested for the purpose of inhibiting the growth of microorganisms in meat (Fang et al. 2017). For example, nisin-containing antimicrobial packaging has been used to retard the growth of the total viable bacteria and lactic acid bacteria in beef burgers stored at 4 °C and prolong their shelf life (Ferrocino et al. 2016). Natrajan and Sheldon (2000) carried out a study to evaluate the potential use of packaging materials as delivery vehicles for carrying and transferring a nisin-containing formulation onto the surfaces of fresh poultry products and demonstrated the efficacy of nisin-coated (100 ug/ml) polymeric films in inhibiting *Salmonella* Typhimurium on fresh chicken thigh skin.

Even so, antimicrobial packages have had limited commercial success so far, except for Japan where Ag-substituted zeolite is the most common antimicrobial agent incorporated into plastics intended for food packaging. Ag-ions inhibit a range of metabolic enzymes and have strong antimicrobial activity (Ščetar et al. 2010). Lee et al. (2011) studied the efficacy of wrapping paper impregnated with silver-containing zeolite to reduce bacterial growth on raw beef, pork, and turkey cuts. Storage on the silver-zeolite paper accounted for the mean reduction in viable cell count of one log cfu/sample for all of these samples when compared with samples stored on the regular butcher paper at 3 days.

The advantage of silver antimicrobial agents is that they can be easily introduced into multiple materials, such as plastics and textiles, making them useful in a wide spectrum of applications, maintaining their antimicrobial activity *in situ*, in which traditional antimicrobial agents would be unstable (Almeida et al. 2015). A comprehensive review of the application of silver nanoparticles (AgNPs) in food packaging was prepared by Simbine et al. (2019). According to their study, silver nanoparticles are promising antimicrobial agents acting against a wide range of microorganisms, including highly pathogenic Gram-positive and Gram-negative bacteria and fungi. However, in spite of all the advantages related to the use of AgNPs, one possible limitation of their use in food packaging lies in their potential migration into/onto the food, leading to possible toxicity problems (Panea et al. 2014). It is, therefore, necessary to carry out migration tests when a new packaging technology based on AgNP is produced (Simbine et al. 2019).

The use of naturally derived antimicrobial agents is important due to the lower perceived risk to the consumer compared to artificial antimicrobials. Essential oils have attracted great attention as natural antimicrobial agents for meat and meat products. The phenolic compounds in essential oils, such as carvacrol, eugenol, and thymol are considered responsible for the observed antimicrobial activity (Jayasena and Jo 2013). Moreover, the addition of plant extracts and essential oils to meat products not only extends the shelf life but also offers health benefits to the consumer through their antimicrobial and antioxidant activities in the human body once ingested (Fang et al. 2017).

The combined effect of essential oils and packaging atmosphere on the quality and safety of meat was also studied. Mahgoub et al. (2019) studied the effect of packaging atmosphere, storage temperature and oregano essential oil on the growth of *Listeria monocytogenes* on ready-to-eat smoked turkey meat. According to their findings, a modified atmosphere (40% CO_2 : 60% N_2) combined with oregano essential oil can be effectively used to control the growth of pathogens in processed food under circumstances where maintaining stable low temperatures is difficult. The positive effect of volatile compounds of oregano essential oil on the shelf life of meat and meat products was reported also by Kerry et al. (2006).

Spoilage microorganisms of meat and poultry

It is well known that the richness and abundance of microbiota present in food products, especially meats, play an important role in the microbial safety and shelf life of the product (Zhao et al. 2015; Cauchie et al. 2020). Raw meat and poultry are highly perishable commodities, which readily support microbial growth even when stored chilled (Säde et al. 2013). This is due to the complex nutrient-rich environment with chemical and physical conditions favourable to bacterial development. Moreover, meat can be contaminated by various types of microorganisms from several sources, such as raw materials, equipment, environment and handling involved in the production process. Abiotic factors (temperature, gaseous atmosphere, pH, etc.) can also contribute to the selection of certain bacteria (Säde et al. 2013; Rouger et al. 2018; Cauchie et al. 2020).

The initial contamination of products, and also the initial level of lactic acid bacteria, is a key factor that can influence the spoilage dynamic during storage. According to a study by Cauchie et al. (2020), microbial counts in minced pork meat from four manufacturers greatly differed, which can be explained by the fact that multiple sources of contamination can contribute to the initial composition of the meat microbiota, including in particular the farm and the slaughterhouse.

Bacterial growth is an important factor that induces the deterioration of meat quality during storage (Gallas et al. 2010; Bassey et al. 2021a). The microbial populations of refrigerated meat are mainly composed of *Pseudomonas* spp., cold-tolerant *Enterobacteriaceae*, lactic acid bacteria (LAB) (such as *Lactobacillus* spp., *Lactococcus* spp., *Leuconostoc* spp., *Carnobacterium* spp., etc.), *Brochothrix thermosphacta*, *Clostridium* spp. and *Weissella* spp. (Casaburi et al. 2014; Cauchie et al. 2020). Other genera isolated frequently from fresh pork meats include *Acinetobacter* spp., *Aeromonas* spp., *Enterococcus* spp., *Moraxella* spp. (Zhao et al. 2015; Cauchie et al. 2020) and *Photobacterium* spp. (Nieminen et al. 2016; Bassey et al. 2021a).

Pseudomonas spp., LAB, and *Enterobacteriaceae* have been considered the dominant spoilage microorganisms in poultry meat. The study by Zhang et al. (2012) showed that *Staphylococcus* spp., *Pseudomonas* spp., *Acinetobacter* spp., *Carnobacterium* spp., *Aeromonas* spp., and *Weissella* spp. were the dominant bacteria in poultry meat. *Enterobacteriaceae* only appeared in samples subjected to storage with high temperature abuse, whereas *Shewanella* spp. and *Psychrobacter* spp. were only detected in samples stored below 4 °C.

The effect of meat and poultry packaging on bacterial communities

Besides the temperature, the type of packaging can influence the bacterial community in fresh meat. Cauchie et al. (2020) studied the effect of food packaging on bacterial communities present in pork meat and found that two different types of packaging were characterized by different microbiota, with only some genera in common. By the end of the shelf life, *Pseudomonas* spp. was more abundant in minced pork samples in overwrap packaging and this genus was replaced by *Brochothrix* spp. in the samples in MAP packaging (30% CO_2: 70% O_2). Other authors also confirm that the use of a CO_2-enriched modified atmosphere has a selective effect on the growth of many microbes developing on MA packaged meat (Säde et al. 2013; Rouger et al. 2018; Bassey et al. 2021a). While high CO_2 levels suppress the growth of aerobic meat spoilage bacteria such as *Pseudomonas* spp., psychrotrophic facultative anaerobic bacteria less sensitive to CO_2 grow to predominate in the microbial community. Therefore, LAB and *Brochothrix thermosphacta* often constitute the largest part of the microbial community on MA packed meat (Säde et al. 2013; Nieminen et al. 2016).

In Europe, raw pork and beef sold in retail is commonly packaged under a high-oxygen modified atmosphere containing 60–80% O_2 and 20–40% CO_2. Oxygen is added to maintain the red colour of meat whereas CO_2 suppresses microbial growth. Despite the effect of CO_2, the shelf life of MAP raw meat is commonly limited by bacterial spoilage (Nieminen et al. 2016). Similarly to other studies, Nieminen et al. (2016) identified LAB (*Carnobacterium*, *Lactobacillus*, *Lactococcus*, *Leuconostoc*, *Weissella*) and/or *B. thermosphacta* as the predominant bacteria in pork packaged under high-oxygen modified atmosphere. Unexpectedly, however, they reported high abundance of *Photobacterium phosphoreum* in pork. This bacterium had rarely been reported in red meat before while being a well-known spoilage organism in fish products. It grows rapidly at refrigeration temperatures and tolerates high concentrations of CO_2 (Nieminen et al. 2016). Moreover, according to Stoops et al. (2015) and Nieminen et al. (2016), *Photobacterium* spp. can predominate in pork packaged in MAP with oxygen concentration as high as > 50%. These data suggest that *Photobacterium* spp. may be more relevant in MAP meat spoilage than previously thought.

The impact of high (50–70%) and low (20–50%) O_2 content in combination with CO_2 atmosphere on bacterial growth was also studied with the conclusion that a high O_2 content in MAP was better for inhibiting key spoilers, such as *Pseudomonas* spp., *Enterobacteriaceae*, LAB, and *B. thermosphacta* (Esmer et al. 2011).

On the other hand, Martínez et al. (2006) reported that fresh pork packages without O_2, either under vacuum or in the presence of an O_2 scavenger, showed the lowest psychrotrophic bacteria counts which did not exceed 7 log CFU/g at 2±1 °C even after 20 days of storage. Similarly, Rogers et al. (2014) concluded that anaerobic packaging extends shelf life properties and desirable sensory attributes throughout the display and temperature abuse.

A recent study by Bassey et al. (2021a) evaluated the effects of MAP on spoilage indexes and on the bacterial population of predominant spoilers in fresh pork loins at super-chilling (−2 °C) storage. They found that the abundance of *Pseudomonas* spp., *Brochothrix* spp., LAB, and *Photobacteria* spp., regarded as predominant spoilers of meat, was in general influenced by the gas composition used in the packages. Significant inhibitions of *Pseudomonas* spp., *Brochothrix* spp., *Serratia* spp., *Hafnia* spp., *Acinetobacter* spp., *Kurthia* spp., and *Kocuria* spp. were detected in samples stored in MAP 70% N_2 : 30% CO_2 over time.

Inhibition of predominant meat spoilers by different MAP compositions was reported by Bassey et al. (2021b) also during chilled storage (4 °C). Their results indicated that 70% O_2 : 30% CO_2 retained more redness content, while 70% N_2 : 30% CO_2 markedly reduced spoilage indicators compared to the control group. Also, a modified atmosphere with 20% O_2 : 60% N_2 : 20% CO_2 inhibited the growth of abundant spoilers, *Pseudomonas* spp. and *Brochothrix* spp.

Potential benefits of various gas ratios of MAP packaging (10% O_2 : 90% N_2, 30% O_2 : 70 % N_2, 20%O_2 : 75% N_2 : 5% CO_2 and air) on freshness of meat stored at −3 °C were studied by Ye et al. (2020). The quality and freshness of pork with no MAP was the worst of all groups. The best overall results for sensory evaluation, colour and bacterial inhibition were recorded for the atmosphere with 30% O_2 : 70% N_2; the downside of this packaging was the relatively serious protein oxidation.

Enterobacteriaceae may play important role in meat spoilage due to their ability to metabolize amino acids to malodorous volatile compounds such as foul-smelling diamines and sulphuric compounds (Säde et al. 2013). Säde et al. (2013) identified *Hafnia* spp. and *Serratia* spp. as the predominant enterobacteria on various raw meat and poultry products in commercial MA packages. Percentage distribution in different products showed that 89% of the *Serratia* spp. originated from products packaged under a high-O_2 MAP containing

CO_2 (25–35%), whereas most (76%) isolates of *Hafnia* originated from anaerobically packed red meat and poultry. They also found relatively high enterobacteria counts on poultry products compared to products from other categories.

Packaging and shelf life of fish

Fresh seafood has become increasingly popular; however, these perishable products suffer from short shelf life, being especially vulnerable from the perspective of food safety. Fish meat perishability is due to its high a_w, neutral pH, and presence of autolytic enzymes. These factors combined with the lower content of connective tissue compared to other flesh foods lead to more rapid spoilage of fish compare to the mammalian muscles (Pereira de Abreu et al. 2010). The rate of deterioration is highly temperature-dependent and can be inhibited by the use of low storage temperature (e.g. fish stored on ice).

Spoilage of fresh fish during storage is mainly caused by enzymatic reactions (microbial and autolytic degradation) generating off-flavours and resulting in unacceptability for human consumption. The microorganisms associated with seafood can be directly related to the fishing area, environmental factors, harvesting methods, storage, and transportation. Additionally, oxidation of polyunsaturated fatty acids is another factor limiting shelf life. The oxidation produces volatile compounds that affect sensory properties, influencing the customer acceptance of fresh fish (Masniyom 2011; Merlo et al. 2019).

Changes in the quality of fish can be monitored by biochemical or enzymatic freshness and microbial changes during handling and storage. The endogenous proteinases play an important role in protein degradation of *postmortem* fish muscle. Apart from endogenous proteases, microorganisms growing on the muscles secrete a wide variety of hydrolytic enzymes, particularly proteinases. *Pseudomonas* spp., are considered to be the main organisms responsible for the deterioration of food proteins. It is why the shelf life of chilled fish is generally limited due to the growth of Gram-negative microorganisms such as *Pseudomonas* spp., *Shewanella putrefaciens*, and *Aeromonas* spp. under aerobic conditions (Masniyom 2011).

Lipolysis, lipid oxidation, and the interaction of the products of these processes with nonlipid components such as protein occurring during storage are additional factors deteriorating the fish meat quality. Endogenous enzymes and microorganisms, mainly phosholypase and triacyl lipase, constitute the dominant source of such reactions. Lipoxygenases and peroxidases are enzymes that oxygenate polyunsaturated fatty acids in fish, converting them to hydroperoxides, which can initiate the auto-oxidation of fatty acids. In the presence of high oxygen content in the package, the rancidity of lipid could be increased, resulting in the generation of fishy off-odour. Prevention of lipolysis and lipid oxidation of fish during storage can be achieved by the incorporation of MAP and combined methods (Masniyom 2011).

Shelf life of iced or chilled fish stored under MAP increases as a result of the extension of the lag phase of several aerobic spoilage bacteria. With fresh fish storage in an oxygen-free MAP, the lipid oxidation and growth of aerobic bacteria can be significantly reduced (Macé et al. 2013; Merlo et al. 2019). Modified atmosphere packaging with CO_2-enriched atmosphere inhibits the growth of respiratory organisms and enables the growth of *Photobacterium phosphoreum* and LAB. Lactic acid bacteria, particularly *Lactococcus piscium* and *Hafnia alvei*, are some of the spoilage bacteria of salmon stored under MAP without O_2 (Merlo et al. 2019). Macé et al. (2013) also identified *Lactococcus piscium,* Gram-negative fermentative bacteria (*Photobacterium phosphoreum*) and *Enterobacteriaceae* (*Serratia* spp.) as the dominant bacterial groups or species at the time of spoilage on salmon steaks stored under vacuum or MAP (50% CO_2 : 50% N_2).

Seafood is traditionally stored under refrigeration in air, which gives a shelf-life ranging from 2 to 10 days, depending upon species, harvest location, season, initial microbiological quality and storage temperature (Masniyom 2011). Modified atmosphere packaging including vacuum packaging has been proven to extend the shelf life and retard the deterioration of refrigerated fish and seafood. Typically, shelf-life is extended by 30–60% for fresh fishery products using atmospheres with elevated levels of CO_2 (Sivertsvik et al. 2002). Pantazi et al. (2008) found that the shelf-life of fresh Mediterranean swordfish kept under a vacuum increased by nine days, which was more than that seven days increase resulting from aerobic packaging.

The MAP requirements for fish packaging are different from the MAP usually used for fresh meat because in this animal product, colour is a less important factor. CO_2 is the most important gas used in MAP of fish, because of its bacteriostatic and fungistatic properties. O_2 is often excluded from the MAP of packaged fishery products. N_2 is used to replace O_2 in packages to delay oxidative rancidity and inhibit the growth of aerobic microorganisms as an alternative to vacuum packaging. The use of oxygen in MAP is normally set as low as possible to inhibit the growth of aerobic spoilage bacteria (Sivertsvik et al. 2002; Masniyom 2011).

Conclusion

This review summarized the available information regarding the characteristics, application types and effect on the shelf life of packaging technologies used for poultry, meat and fish, with a focus on MAP and different types of active packaging. In the packaging of meat, especially red meat, the colour is a very important factor influencing purchase decisions; therefore, high-oxygen atmosphere packaging is often used to maintain the required sensory properties. Packaging requirements for fresh fish are different – oxygen is often excluded from the package to delay oxidative rancidity and inhibit the growth of aerobic microorganisms. A properly designed MAP can preserve organoleptic characteristics while, at the same time, ensuring the safety and prolonging the shelf life of the product by inhibiting the growth of pathogenic and spoilage microorganisms. The conditions of food storage count among the most important factors in the Hurdle effect theory, preventing the growth of microorganisms. Although MAP offers many advantages, it cannot replace the good hygiene and handling practices throughout the food chain. Without proper control of storage temperatures and maintaining the cold chain, the benefits of MAP may be lost.

Aknowledgements

The review was supported by the NAZV project No. QK21020245.

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