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Opportunities for bio-based packaging technologies to improve the quality and safety of fresh and further processed muscle foods

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Abstract

It has been well documented that vacuum or modified atmosphere packaging materials, made from polyethylene- or other plastic-based materials, have been found to improve the stability and safety of raw or further processed muscle foods. However, recent research developments have demonstrated the feasibility, utilization, and commercial application of a variety of bio-based polymers or bio-polymers made from a variety of materials, including renewable/sustainable agricultural commodities, and applied to muscle foods. A variety of these bio-based materials have been shown to prevent moisture loss, drip, reduce lipid oxidation and improve flavor attributes, as well as enhancing the handling properties, color retention, and microbial stability of foods. With consumers demanding more environmentally friendly packaging and a desire for more natural products, bio-based films or bio-polymers will continue to play an important role in the food industry by improving the quality of many products, including fresh or further processed muscle foods.

Keywords: Packaging; Edible; Bio-based polymers; Biopolymers; Muscle foods

1. Introduction

The purpose of food packaging is to preserve the quality and safety of the food it contains from the time of manufacture to the time it is used by the consumer (Dallyn & Shorten, 1998). An equally important function of packaging is to protect the product from physical, chemical, or biological damage (Dallyn & Shorten, 1998). The most well-known packaging materials that meet these criteria are polyethylene- or co-polymer based materials, which have been in use by the food industry for over 50 years. These materials are not only safe, inexpensive, versatile, but also flexible (Tice, 2003). Global production of packaging materials are estimated at more than 180 million tons per year, with growth and demand increasing annually (Tice, 2003). Within the plastic packaging market, food packaging is the largest growing sector (Comstock, Farrell, Godwin, & Xi, 2004). It is estimated that of the $100 billion packaging market in the United States, 70% is attributed to beverage and food production (Comstock et al., 2004). However, one of the limitations with plastic food packaging materials is that it is meant to be discarded, with very little being recycled (Comstock et al., 2004). In fact, during the 1990s less than 10% of all plastic packaging materials (not including bottles) was recycled by consumers (Comstock et al., 2004). The presence of these types of packaging materials in landfills can be problematic on many fronts. First, if plastic is not recycled, these items end up in landfills, where they can last forever and never degrade. Secondly, many countries are faced with a decrease in landfill space, especially in densely populated areas (Comstock et al., 2004). Thirdly, existing landfills may be unable to meet new regulatory guidelines set forth by the US Environmental Protection Agency, and may end up closing (Environmental Protection Agency, 2006). So, finding landfills for consumer and industrial waste may become more difficult in the future (Comstock et al., 2004).

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Another factor to consider is the reliance on petroleum products in the production of plastic packaging materials. With rising petroleum costs, there is concern with finding cost-effective ways to manufacture packaging materials. Weber, Haugaard, Festersen, and Bertelsen (2002) state that "polymers and materials used for food-packaging today consist of a variety of petroleum-derived plastic materials, metals, glass, paper and board, or combinations hereof. With the exception of paper and board, all of these packaging materials are actually based on non-renewable materials, implying that at some point, more alternative packaging materials based on renewable resources have to be found". The authors also point out that "naturally-derived resources" are becoming more essential in the production of these industrial products, and that bio-based packaging materials are beginning to replace petroleum-based packaging materials in the food industry (Weber et al., 2002).

In addition to the above environmental issues, food packaging has been impacted by notable changes in food distribution, including globalization of the food supply, consumer trends for more fresh and convenient foods, as well a desire for safer and better quality foods. Given these and previously mentioned issues, consumers are demanding that food packaging materials be more natural, disposable, potentially biodegradable, as well as recyclable (Lopez-Rubio et al., 2004).

To meet the growing demand of recyclable or natural packaging materials and consumer demands for safer and better quality foods, new and novel food-grade packaging materials or technologies have been and continue to be developed. Examples of these packaging materials include bio-based polymers, bioplastic or biopolymer packaging products made from raw materials originating from agricultural or marine sources (Cha & Chinnan, 2004). These types of packaging materials include, but are not limited to starch, cellulose, chitosan/chitin, protein (animal, plant-based), or lipids (animal, plant-derived, etc.). Within this context of packaging, edible films, gels or coatings may be considered biopolymers with some biodegradable properties. Another example of a biopolymer is polylactic acid (PLA). Other biopolymers have been made from marine prokaryotes, chemical synthesis, as well as from by-products of other microorganisms (ie., fungal exopolysaccharides) (Cha & Chinnan, 2004).

In addition to the development of packaging materials from these polymers, researchers are employing various types of packaging materials to be active, intelligent, or interactive. Such food packaging systems have been developed for a variety of chemical (chelators, antioxidants, flavors, essential oils, etc.) or antimicrobial compounds (bacteriocins, organic acids, lysozyme, etc.); gas (i.e. ethylene, carbon dioxide, oxygen, nitrogen, etc.) scavengers or emitters; humidity absorbers or controllers; aroma absorbers or emitters; or active enzyme systems (Lopez-Rubio et al., 2004). When applied, research has demonstrated that packaging can enhance the quality or safety of the food, slow deterioration, and impart desirable characteristics to the food.

Given the wealth of information in the field of food packaging as well as notable and recent developments in the area of active, interactive, and intelligent packaging systems, this review will address the implementation of biopolymers (i.e. edible gels, films, or coatings), bio-based plastic packaging materials, as well as the incorporation of antimicrobials into these packaging materials to improve the quality and/or safety of fresh or further processed meat and poultry products.

2. Bio-based polymers or biopolymers

Typically, bio-based polymers or biopolymers are developed from renewable resources (Comstock et al., 2004; Weber et al., 2002; Fig. 1). Examples of renewable resources used in the manufacture of these types of polymers include polysaccharides (i.e. starch, alginates, pectin, carrageenans, chitosan/chitin), proteins (casein, whey, collagen, gelatin, corn, soy, wheat, etc.), and lipids (fats, waxes, or oils, etc.; Comstock et al., 2004; Cutter & Sumner, 2002). Polymers, such as polylactate (PLA) or polyesters, also may be synthesized from biologically-derived monomers, while microorganisms also can produce polymers such as cellulose, xanthan, curlan, or pullulan (Comstock et al., 2004; Kandemir et al., 2005). Researchers also have further categorized biopolymers based on the ability to be compostable or biodegradable (Comstock et al., 2004). It is important to note that while some bio-based packaging materials may be biodegradable, not all biodegradable materials are bio-based (Weber et al., 2002).

Recent technological advances also have allowed biopolymers to be processed similarly to petroleum-based plastics, whether in sheets, by extrusion, spinning, injection molding, or thermoforming (Comstock et al., 2004). Notable advances in biopolymer production, consumer demand for more environmentally-friendly packaging, and technologies that allow packaging to do more than just encompass the food are driving new and novel research and developments in the area of packaging for muscle foods.

3. Edible gels, films and coatings

In the last 50 years, considerable research has been conducted to develop and apply bio-based polymers made from a variety of agricultural commodities and/or wastes to food products. Edible coatings and films made from a number of these commodities have been developed that offer a variety of advantages to fresh and further processed meats and poultry such as edibility, biocompatibility, aesthetic appearance, and barrier properties (Han, 2000, 2002). Because edible films are considered a packaging as well as a food component, they should fulfill a number of requirements, such as: good sensory qualities; high barrier and mechanical efficiencies; biochemical, physico-chemical, and microbial stability, non-toxic, simple, non-polluting,

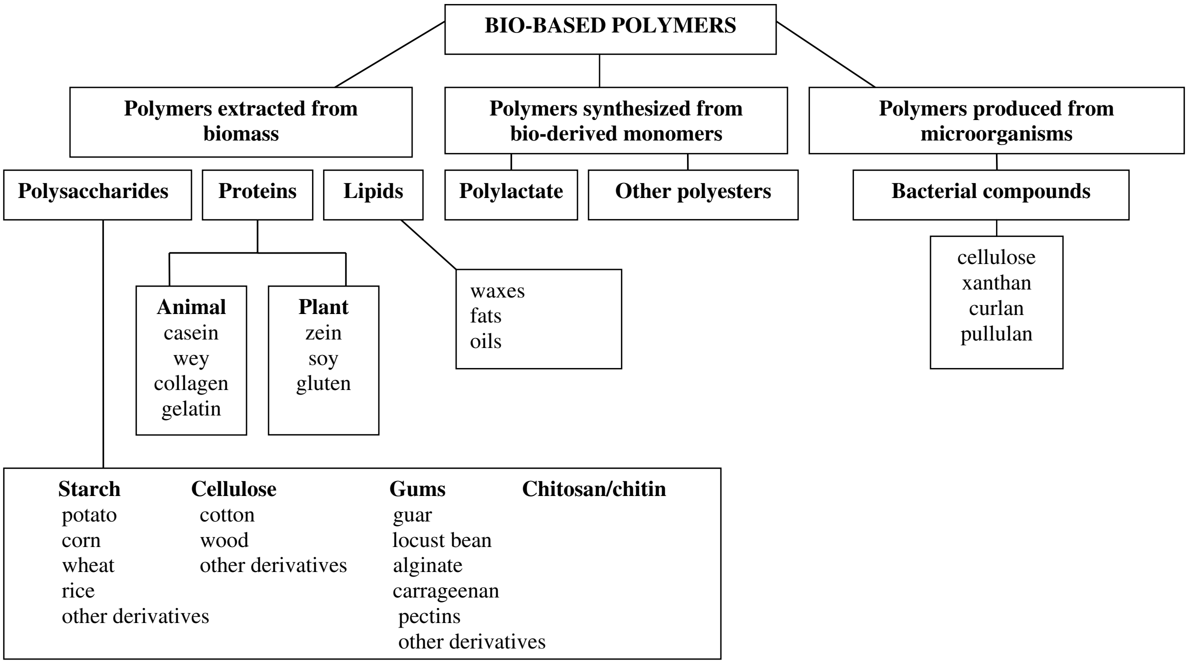

Fig. 1. Different categories of bio-based materials (adapted from Weber et al., 2002).

and low cost (Debeaufort, Quezada-Gallo, & Voilley, 1998).

From a quality standpoint, studies with bio-based polymers have indicated that improvements can be made to muscle foods by reducing moisture loss, minimizing lipid oxidation, preventing discoloration, and reducing drip (Gennadios, Hanna, & Kurth, 1997). Also, by incorporating antimicrobials into edible coating, gels, or films, the safety and overall microbiological attributes (i.e. shelf life, spoilage) of muscle foods also can be controlled.

3.1. Application of edible films

The application of edible films to muscle foods is accomplished by indirect or direct application. For direct application, a number of methods have been employed, including but not limited to foaming, dipping, spraying, casting, brushing, wrapping, or rolling (Cutter & Sumner, 2002; Donhowe & Fennema, 1994; Grant & Burns, 1994). For foam applications, a foaming agent may be added to the coating or compressed air blown into the applicator tank (Cutter & Sumner, 2002; Donhowe & Fennema, 1994; Grant & Burns, 1994). Then, the edible foam is applied to the muscle food by flaps or brushes as it moves over rollers (Cutter & Sumner, 2002; Donhowe & Fennema, 1994; Grant & Burns, 1994). In some instances, submerging the muscle food into a tank of the emulsion may work best, especially when applying several coats, when smoothing out irregular surfaces, or when costs need to be controlled (Cutter & Sumner, 2002; Donhowe & Fennema, 1994; Grant & Burns, 1994). After dipping, the excess coating usually drips off and the remaining material is allowed to set or solidify on the muscle food (Cutter & Sumner, 2002; Donhowe & Fennema, 1994). In some cases, a heated air drier may be applied to speed up the setting process or to remove excess water (Cutter & Sumner, 2002; Grant & Burns, 1994).

When a thinner, more uniform edible film is required for certain surfaces, films may be best applied by spraying (Cutter & Sumner, 2002). In fact, early coating procedures involved sprays, with further distribution over food surfaces via rollers or brushes, followed by tumbling to evenly spread the coating (Cutter & Sumner, 2002; Grant & Burns, 1994). Spray applications are also suitable when applying films to a particular side or when a dual application must be used for cross-linking, as is practiced with alginate coatings (Donhowe & Fennema, 1994; Siragusa & Dickson, 1993). Just as with foams, heated air can be applied after spraying to speed up the drying process or improve uniform distribution on the surfaces (Cutter & Sumner, 2002; Grant & Burns, 1994).

With regard to indirect application of bio-based films to muscle foods, casting technologies may be employed. In this process, film-forming solutions may be poured onto a smooth, flat and level surface, with or without a mold to contain the solution, and allowed to dry or set (Cutter & Sumner, 2002). When performed in this manner, casting produces freestanding films with a desired thickness, smoothness, and flatness (Cutter & Sumner, 2002; Donhowe & Fennema, 1994). When handled or processed as described, cast films may be firm and flexible enough to be wrapped around food surfaces (Cutter & Sumner, 2002).

When it comes to applying films, gels or coatings to muscle foods, they should exhibit a number of functional properties, such as moisture barrier ability, water or lipid solubility, color, appearance, transparency, desired mechanical or rheological characteristics, and be non-toxic (Cutter & Sumner, 2002; Guilbert, Gontard, & Gorris, 1996). These properties can be influenced by the addition of compounds, including plasticizers, cross-linking agents, antimicrobials, antioxidants, or textural additives (Cutter & Sumner, 2002). Not only should these films exhibit flexibility, permeability, gas and solute migration, or porosity following incorporation of these additives, but these films also should be resistant to breakage and abrasion (Cutter & Sumner, 2002; Guilbert et al., 1996).

3.2. Polysaccharide films

Polysaccharide films are made from starch, alginate, cellulose ethers, chitosan, carageenan, or pectins and impart hardness, crispness, compactness, thickening quality, viscosity, adhesiveness, and gel-forming ability to a variety of films (Baldwin, Nisperos, & Baker, 1995; Ben & Kurth, 1995; Cutter & Sumner, 2002; Glicksman, 1983; Nisperos-Carriedo, 1994; Whistler & Daniel, 1990). While lipid films could produce anaerobic conditions, polysaccharide-derived films exhibit excellent gas permeability properties, resulting in desirable modified atmospheres that enhance the shelf life of the product without creating anaerobic conditions (Baldwin et al., 1995). Additionally, polysaccharide films and coatings can be used to extend the shelf-life of muscle foods by preventing dehydration, oxidative rancidity, and surface browning (Nisperos-Carriedo, 1994). Because of the make up of the polymer chains, polysaccharide films can exhibit low gas permeability; but their hydrophilic nature makes them poor barriers for water vapor (Ben & Kurth, 1995). Interestingly, polysaccharide films have been available commercially for the Japanese meat industry for a number of years (Labell, 1991). When applied to wrapped meat products and subjected to smoking and steam, the polysaccharide film actually dissolves and becomes integrated into the meat surface. Meats treated with the polysaccharide film in this manner exhibited higher yields, improved structure and texture, and reduced moisture loss (Labell, 1991; Stollman, Hohansson, & Leufven, 1994).

3.3. Starch

Starch, composed of amylose and amylopectin, is primarily derived from cereal grains, potatoes, tapioca, or arrowroot (Baldwin et al., 1995; Cutter & Sumner, 2002; Nisperos-Carriedo, 1994). Starch-based films exhibit physical characteristics similar to plastic films in that they can be odorless, tasteless, colorless, non-toxic, biologically absorbable, semi-permeable to carbon dioxide, and resistant to passage of oxygen (Nisperos-Carriedo, 1994; Rankin, Wolff, Davis, & Rist, 1958). High amylose starch films have been made that are flexible, oxygen impermeable, oil resistant, heat-sealable, and water soluble (Gennadios et al., 1997). Not only did the films protect meat products during frozen storage, but also dissolved during thawing and cooking (Gennadios et al., 1997).

Since the water activity (a_w) is critical for microbial, chemical, and enzymatic activities, studies have demonstrated that films can resist the migration of moisture into the meat or poultry product during storage (Wong, Camirand, & Pavlath, 1994). For example, edible starch-based films can retard microbial growth by lowering the a_w within the package, thereby reducing drip loss of meat products and binding water that otherwise would be available for microbial growth (Wong et al., 1994). Water permeability studies also were conducted for two biodegradable, polymeric films made from starch derivatives and compared to commercially available polyvinyl chloride films used in the packaging of beef steaks (PVC; Cannarsi, Baiano, Marino, Sinigaglia, & Del Nobile, 2005). The researchers demonstrated that when compared to beef steaks wrapped in PVC control films, these biodegradable films slowed down the migration of moisture from the steaks, but with no changes to the microbiological profile or subsequent shelf life of the product (Cannarsi et al., 2005).

3.4. Alginate

Alginates are derived from seaweed, and possess good film-forming properties that make them particularly useful in food applications (Cutter & Sumner, 2002; Kester & Fennema, 1986; Nisperos-Carriedo, 1994). Divalent cations (calcium, magnesium, manganese, aluminum, or iron) are used as gelling agents in alginate film formation (Cutter & Sumner, 2002; Gennadios et al., 1997; Kester & Fennema, 1986). Of the cations evaluated, calcium appears to be more effective in gelling alginates than the others (Kester & Fennema, 1986). Materials, such as modified starches, oligosaccharides, or simple sugars also have been found to improve properties of alginate films (Gennadios et al., 1997).

When investigating desirable properties attributed to alginate films, most researchers have reported improvements to moisture retention, reduction in shrink, improved product texture, juiciness, color, and odor of treated muscle foods (Cutter & Sumner, 2002). However, bitterness imparted by the calcium chloride necessary to set the alginate, was unacceptable from a sensory standpoint (Allen, Nelson, Steinberg, & McGill, 1963). To combat this sensory issue, calcium propionate has been used with prolonged gelling and found to result in a more acceptable flavor (Hartal, 1966). Other researchers have demonstrated that alginate coatings reduced microbial counts, had acceptable flavor, tenderness, appearance and did not affect cooking losses, flavor, odor, or overall acceptability of coated beef, pork, lamb, and poultry products (Cuq, Gontard, & Guilbert, 1995; Lazarus, West, Oblinger, & Palmer, 1976; Mountney & Winter, 1961; Nisperos-Carriedo, 1994; Williams, Oblinger, & West, 1978). Another study found that alginate coatings retarded oxidative off-flavors, improved flavor and juiciness in re-heated pork patties (Wanstedt, Seideman, Connelly, & Quenzer, 1981). Other researchers have extended the shelf life of shrimp, fish, and sausage with alginate coatings (Daniels, 1973; Earle, 1968; Earle & Snyder, 1966; Earle & McKee, 1976) and improved adhesion between batter and muscle food surfaces (Fischer & Wong, 1972). Hargens-Madsen (1995) also treated pork chops with alginate–starch coatings containing the natural antioxidant tocopherol and found them to be juicier and less susceptible to lipid oxidation. And finally, sodium alginate coatings extended the shelf life of salted and dried mackerel (Cutter & Sumner, 2002; Shetty, Bhaskar, Bhandary, & Raghunath, 1996).

3.5. Carrageenan

Carrageenan is a complex mixture of several polysaccharides. To date, there are only a limited number of studies addressing the use of carrageenan with muscle foods. Carrageenan-based coatings have been used to prolong the shelf life of a variety of muscle foods including poultry and fish (Meyer, Winter, & Weister, 1959; Pearce & Lavers, 1949; Stoloff, Puncochar, & Crowther, 1948). Additional studies have demonstrated that antioxidants, such as gallic or ascorbic acids or lecithin, salt or antibiotics, can be added to the coatings to improve the quality and microbiological stability of muscle foods (Allingham, 1949; Meyer et al., 1959; Pearce & Lavers, 1949; Stoloff et al., 1948).

3.6. Cellulose ethers

Cellulose is a non-digestible component of plant cell walls. In the manufacture of edible films, cellulose-based films tend to be water soluble, resistant to fats and oils, tough, and flexible (Baldwin, Nisperos, Hagenmaier, & Baker, 1997; Cutter & Sumner, 2002; Krumel & Lindsay, 1976). Research studies have demonstrated that cellulose-based films applied to muscle foods can reduce oil uptake during frying, minimize run-off during cooking, and reduce moisture loss when applied as glazes for poultry and seafood (Baker, Baldwin, & Nisperos-Carriedo, 1994; Cutter & Sumner, 2002; Meyers, 1990). Coatings made with ethylcellulose and lipids were transparent and readily peelable, prevented desiccation, and extended the shelf life of beefsteaks (Ayers, 1959). While cellulose-based films have demonstrated mechanical, oxygen barrier, and oil barrier properties for foods such as pizza and ice cream cones, very little information exists for application to fresh or further processed muscle foods (Gennadios et al., 1997).

Cellulose casings also are widely used by the meat industry in the manufacture of ready-to-eat meat and poultry products, including frankfurters, sausages, bologna, and other small diameter meat products subject to thermal processing. Cellulose casings are designed to contain the uncooked meat emulsion, allow for heat penetration and smoke permeability, and maintain the form of a long tubular product. While not considered edible, cellulose casings used in this manner are removed from the meat product and the casings disposed in landfills or enzymatically treated to assist in disposal (Cumba & Bellmer, 2005).

3.7. Pectin

Pectins are a group of plant-derived polysaccharides that appear to work well with low-moisture foods, but are poor moisture barriers (Baldwin et al., 1997). Currently, very little information exists to the application of pectin-based edible films on muscle foods. For example, one study conducted by Stubbs and Cornforth (1980) demonstrated that a calcium pectinate gel coating reduced cooler shrinkage and bacterial growth on beef plates as compared to untreated samples.

3.8. Agar

Another seaweed-derived polysaccharide is agar. Used extensively in microbiological media to provide firmness, agar exhibits characteristics that make it useful for coating meats. It forms strong gels characterized by melting points far above the initial gelation temperature (Cutter & Sumner, 2002; Gennadios et al., 1997; Sanderson, 1981; Whistler & Daniel, 1985). A combination of antibiotics with agar coatings extended the shelf life of coated poultry (Meyer et al., 1959) and beef (Ayers, 1959), but did not reduce moisture loss. Recently, addition of the bacteriocin nisin to agar coatings in combination with food grade chelators (EDTA, citric acid, or polyoxyethylene sorbitan monolaureate) reduced the levels of *Salmonella typhimurium* on poultry surfaces 0.4–2.1 $\log_{10}$cycles (Natrajan & Sheldon, 2000a, 2000b).

3.9. Chitin/chitosan

Chitosan is an edible and biodegradable polymer derived from chitin, the major organic skeletal substance in the exoskeleton of arthropods, including insects, crustaceans, and some fungi (Chen, Yeh, & Chiang, 1996; Cutter & Sumner, 2002; Nisperos-Carriedo, 1994; Suyatma, Copinet, Tighzert, & Coma, 2004). Next to cellulose, chitosan is the most abundant natural polymer available (Vartiainen et al., 2004). Some desirable properties of chitosan are that it forms films without the addition of additives, exhibits good oxygen and carbon dioxide permeability, as well as excellent mechanical properties (Suyatma et al., 2004). Chitosan not only acts as a chelator in biological systems, but also exhibits antimicrobial activity against bacteria yeasts, and molds (Vartiainen et al., 2004). However, one disadvantage with chitosan is its high sensitivity to moisture. Chitosan also inhibits a number of microorganisms and can produce semi-permeable coatings (Cutter & Sumner, 2002; Nisperos-Carriedo, 1994). These inherent properties, coupled with the ability to form films, alone or in combination with other polymers, make chitosan a desirable food packaging material. Additional research with chitin/chitosan and antimicrobial properties is discussed later in this review.

3.10. Lipid films

Larding, or enrobing muscle foods with fats, has been performed primarily to reduce shrinkage of the food product, as well as to provide oxygen or moisture barriers (Kamper & Fennema, 1984). Fats are used to coat poultry, shrimp, meat patties, and sausages (Hernandez, 1994; Kroger & Igoe, 1971). Waxes and other types of fat-based oils also have been added to protein- or polysaccharide-based films to impart flexibility, to improve coating characteristics, or to prevent sticking during cooking (Baldwin et al., 1995). Edible lipid or resin coatings also may be prepared from waxes (e.g., carnauba, beeswax, and paraffin), oils (vegetable, animal, and mineral), and surfactants (Baldwin et al., 1995; Cutter & Sumner, 2002).

There are a number of advantages for coating foods with lipids. Lipids not only impart hydrophobicity, cohesiveness, and flexibility, but they also make excellent moisture barriers due to the tightly packed crystalline structure of lipids that naturally restricts the passage of water vapor molecules (Cutter & Sumner, 2002; Hernandez, 1994; Kester & Fennema, 1986). Several studies have demonstrated advantages to coating fresh, frozen or further processed muscle foods with lipid-based films to preserve quality.

McGrath (1955) demonstrated that and edible wax not only reduced discoloration and labor, but also offered a transparent film capable of withstanding rugged supermarket handling. Letney (1958) demonstrated that meats treated with waxes exhibited a longer shelf life at refrigerated conditions, lessened surface dehydration, and maintained meat color. Ayers (1959) demonstrated that a lipid-based film reduced off-odors and retained moisture, yet resulted in an unappealing meat color. Anderson (1960, 1961a, 1961b) demonstrated that a lipid-based emulsion sprayed or dipped directly onto frozen meats or fish reduced moisture loss and freezer burn, while maintaining color integrity. Brissey and Hill (1961) applied lipid-based coatings to whole cuts of meat, processed with artificial casings, smoked and heated, as a means of keeping the meat and casing separate. Sleeth and Furgal (1965) mixed lard and tallow with an antioxidant, coated freeze-dried and fresh meat, including beef steaks, pork chops, and beef cubes, and demonstrated lower thiobarbituric acid levels than untreated controls. When Schneide (1972) applied fats to the surfaces of beef, veal, pork steaks, and fish fillets, storageability and organoleptic properties were improved and no moisture loss was demonstrated. Griffin et al. (1987) and Leu et al. (1987) found no differences in the storage life (microbial growth, color, or odor) of vacuum packaged steaks or roasts treated with a lipid-based film after 4 and 7 weeks of storage at 2 °C, respectively. Stemmler and Stemmler (1976) prolonged the freshness, color, aroma, tenderness, and microbiological stability of fresh beef and pork cuts with a lipid-based film. Heine, Wüst, and Kamp (1979) reported that a mixture of mono-, di- and triglycerides applied to fresh beef and pork pieces and stored at 2 °C for 14 days retained desirable color and did not exhibit appreciable weight loss.

Carnauba, beeswax, and candelilla waxes also have been successfully used to coat frozen meat pieces and extend storage without substantial dehydration (Cutter & Sumner, 2002; Daniels, 1973). Other researchers also have demonstrated that animal-based fats or vegetable oils can be used as flavor carriers or impervious moisture coatings to a variety of fresh, frozen, or cooked muscle foods (Baldwin et al., 1995; Baldwin et al., 1997; Bauer & Neuser, 1969; Bauer, Neuser, & Pinkalla, 1968; Feuge, 1955; Hernandez, 1994; Kroger & Igoe, 1971; Zabik & Dawson, 1963).

Despite these advantages, lipid-based films at higher storage temperatures may exhibit lower permeability to gases such as oxygen, carbon dioxide, and ethylene, leading to potentially anaerobic conditions which may present food safety issues, as well as lack structural integrity, and poor adherence to hydrophilic surfaces (Baldwin et al., 1995; Ben & Kurth, 1995; Hernandez, 1994). Lipid-based films also are subjected to oxidation, cracking, flaking, retention of off-flavors, as well as bitter aftertastes (Gennadios et al., 1997; Hirasa, 1991; Morgan, 1971; Zabik & Dawson, 1963).

3.11. Protein films

Casein, whey protein, gelatin/collagen, fibrinogen, soy protein, wheat gluten, corn zein, and egg albumen have been processed into edible films (Ben & Kurth, 1995). Protein-based films adhere well to hydrophilic surfaces, provide barriers for oxygen and carbon dioxide, but do not resist water diffusion (Baldwin et al., 1995; Cutter & Sumner, 2002; Gennadios & Weller, 1990; Han, 2002).

Two milk proteins, casein and whey, have been used in the manufacture of edible films. These proteins are desirable as components of these films because of their nutritional value, excellent mechanical and barrier properties, solubility in water, ability to act as emulsifiers, and because of their industrial surplus (Khwaldia, Perez, Banon, Desobry, & Hardy, 2004). While a considerable amount of research has been conducted with films made from milk proteins on fruits and vegetables and other dairy foods, there are limited studies addressing the application of these films on muscle foods. In one series of studies, casein films were found to reduce moisture loss, delayed lipid oxidation, and reduced peroxide values in frozen salmon (Khwaldia et al., 2004). In another recent development, a USDA-ARS scientist demonstrated that if casein was mixed with water and glycerol and left to dry, a water-resistant, flexible, film like material was formed (Tomasula, 2002). This film not only locked in moisture in some foods, but also was found to be a durable barrier to outside substances (Tomasula, 2002). The author proposed to add flavorings, vitamins, or minerals to the film in order to enhance flavor and nutritional properties of foods (Tomasula, 2002).

Despite the advantages to using proteins in film formation, research has indicated that enzymes associated with muscle foods can degrade protein films (Gennadios et al., 1997). Additionally, the application of protein films to muscle foods may present health problems, especially for individuals with food allergies associated with milk, egg, peanut, soybean, or rice proteins (Cutter & Sumner, 2002; Gennadios et al., 1997).

3.12. Gelatin/collagen

Edible films also may serve as gas and solute barriers, thereby improving the quality and shelf life of muscle foods (Wong et al., 1994). One example of such a film is gelatin which is reported to have better oxygen barrier properties when combined with other types of films (Gennadios, 2002). In one study, Villegas, O'Connor, Kerry, and Buckley (1999) subjected cooked ham and bacon to gelatin dips (2%, 4%, and 6%), packaged them in oxygen permeable or vacuum packaging films, and stored them under frozen conditions for seven months. Results from these experiments demonstrated that gelatin dips significantly improved oxidative and color stability of the treated products, as compared to untreated controls. Additional studies have demonstrated that gelatin can be used to carry antioxidants, to reduce oxidation, enhance color stability, to retain flavor, taste, and aroma of foods during refrigerated or frozen storage (Gennadios et al., 1997). Gelatin films have been used as a delivery system for applying antioxidants to poultry or applied directly to poultry meat surfaces or processed meats to prevent microbial growth, salt rust, grease bleeding, handling abuse, water transfer, moisture loss, and oil adsorption during frying (Childs, 1957; Gennadios et al., 1997; Klose, Mecchi, & Hanson, 1952). Despite these successes, gelatin lacks strength and requires a drying step to form more durable films (Daniels, 1973).

The use of collagen-based films has been proposed for processed meats, including hams, netted roasts, roast beef, fish fillets, and meat pastes (Gennadios et al., 1997). Currently, the meat industry currently uses collagen films during the processing of meat products. When heated, intact collagen films can form a "skin" or edible film that becomes an integral part of the meat product (Cutter & Miller, 2004; Gennadios et al., 1997). These commercially available collagen films have been purported to reduce shrink loss, increase permeability of smoke to the meat product, increase juiciness, allow for easy removal of nets after cooking or smoking, and absorb fluid exudate (Cutter & Miller, 2004; Gennadios et al., 1997). Protein coatings derived from collagen also have been used to reduce transport of gas and moisture in meats (Baker et al., 1994; Cutter & Sumner, 2002).

3.13. Cereal and oilseed proteins

Limited information exists on the use of cereal and oilseed proteins as edible films for meats. Corn zein coatings reduced lipid oxidation in precooked pork chops, but did not reduce moisture loss (Cutter & Sumner, 2002; Hargens-Madsen, 1995). Addition of an antioxidant, emulsifier, and plasticizer to corn zein films was found to reduce rancidity, yet produced off-flavors in cooked turkey breast slices (Cutter & Sumner, 2002; Herald, Hachmeister, Huang, & Bowers, 1996). In another study, soy films were not as effective as phosphate in preventing development of warmed-over flavor in precooked chicken breast (Cutter & Sumner, 2002; Kunte, 1996). Wu et al. (2000) coated precooked beef patties with wheat gluten or soy protein coatings and demonstrated that both coatings were as effective as polyvinyl chloride film in reducing moisture loss after 3 d of refrigerated storage (4 °C). Both protein coatings also controlled lipid oxidation in coated samples as compared to non-coated controls (Cutter & Sumner, 2002; Wu et al., 2000).

4. Composite films

When it comes to improvements in edible film technologies, most research has addressed film formulations using various combinations of edible materials. Two or more materials can be combined to improve gas exchange, adherence to coated products, or moisture vapor permeability properties (Baldwin et al., 1995). Composite films consisting of lipids and a mixture of proteins or polysaccharides take advantage of the individual component properties. In doing so, these individual or combined films can be applied as emulsions or bilayer films (Cutter & Sumner, 2002). Additionally, plasticizers can be used to modify film mechanical properties, thereby imparting desirable flexibility, permeability, or solubility to the resulting film (Ben & Kurth, 1995). For example, adding glycerol, polyethylene glycol, or sorbitol to a film composition can reduce brittleness (Ben & Kurth, 1995).

In another example of composite films, a combination of vegetable oils, glycerin, citric acid, and antioxidants prevented rancidity by acting as a moisture barrier, restricting oxygen transport, and serving as a carrier for antioxidants to various foods (Baldwin et al., 1995; Cutter & Sumner, 2002). In another study, barrier properties were determined for caseinate films that were treated with a lipid or an enzyme and held at 4 °C and 90% relative humidity (Ben & Kurth, 1995). Lipid addition notably improved moisture barrier properties, but the films appeared slightly cloudy, such that when these particular films were applied to meat surfaces, the appearance of the meat surface was unacceptable (Ben & Kurth, 1995). Subsequent addition of three enzymes to sodium caseinate produced a cross-linked protein film with limited resistance to water vapor and oxygen, did not alter the color of the meat, and also prevented drip loss (Ben & Kurth, 1995). Further research demonstrated that sealing and cooking meat with this enzyme-treated protein gel produced a juicier product, reduced packaging waste and handling by negating the use of absorbent pads, and presented a more attractive product (Ben & Kurth, 1995). And finally, Wong, Gastineau, Gregorski, Tillin, and Pavlath (1992) demonstrated that a chitosan-lauric acid film was less permeable to water vapor, but more permeable to gases than chitosan alone. The authors speculated that the microstructure of this film consisted of a sheet-like arrangement stacked in layers, thereby producing an efficient barrier to moisture (Wong et al., 1992). If these types of films are to be considered as alternatives to plastic packaging, future research should determine the edible nature of these composite films and overall consumer acceptability.

5. Polylactic acid films

Polylactic acid (PLA) is a biodegradable polymer, made primarily from renewable agricultural resources (i.e. corn) following fermentation of starch and condensation of lactic acid (Krishnamurthy, Demirci, Puri, & Cutter, 2004). PLA is composed of chains of lactic acid and exhibits tensile strength comparable to other commercially available polymers (Holbert & Taylor, 1997; Krishnamurthy et al., 2004). In addition to its strength, biodegradability, and compostability, PLA polymers also are resistant to oil-based products, are sealable at lower temperatures, and can act as flavor or odor barriers for foodstuffs (Holbert & Taylor, 1997; Krishnamurthy et al., 2004).

Currently, very little research exists to address the application of PLA to improve the quality of muscle foods. Suyatma et al. (2004) attempted to combine the water vapor barrier properties of chitosan with the hydrophobic biodegradable properties of PLA. While the study demonstrated that the incorporation of PLA into chitosan improved water barrier properties and decreased water sensitivity of the chitosan films, tensile strength and other mechanical and thermal properties were not improved (Suyatma et al., 2004). In additional experiments, the authors demonstrated that a phase separation occurred, thereby proving the incompatibility of the two materials (Suyatma et al., 2004).

Several additional studies have demonstrated the effect of PLA, alone or in combination with other antimicrobials to inhibit microorganisms on fresh or further processed meat products. In 2002, Mustapha, Ariyapitipun, and Clarke demonstrated the synergistic effect of 2% low molecular weight polylactic acid alone or in combination with lactic acid or nisin against *Escherichia coli* O157:H7 on raw beef during irradiation and during refrigerated storage. While the authors demonstrated inhibition against the pathogen on beef using PLA or lactic acid, as well as combinations of PLA with lactic acid and nisin, the authors concluded that the antimicrobial effect of PLA was not significantly different than that of lactic acid alone. In another study, Chellappa (1997) examined the effect of PLA for reducing pathogens on raw meat. *E. coli* O157:H7, *Listeria monocytogenes*, *S. typhimurium*, or *Yersinia enterocolitica* associated with lean beef surfaces 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. When applied to ground beef, ground pork or breakfast sausage inoculated with *E. coli* O157:H7 and subjected to long term refrigerated storage, PLA treatments did result in up to a $1.7 \log_{10}$ reduction of the pathogen (Allanson, 2000). In 2004, Krishnamurthy, Demirci, Puri, and Cutter demonstrated that low dose PLA, in combination with low-dose irradiation (2.0 kGy), followed by long term refrigerated storage could effectively reduce populations of *E. coli* O157:H7 and *S. typhimurium* up to $5 \log_{10} \mathrm{CFU/cm}^2$ (99.999%) on beef surfaces. Subsequent experiments on PLA also demonstrated that irradiation did not affect the tensile strength of the packaging materials (Krishnamurthy et al., 2004).

6. Antimicrobial films

The use of bio-based, polymer-based films as antimicrobial delivery systems to reduce undesirable bacteria in foodstuffs is not a novel concept. Various approaches have been proposed and demonstrated for the use of these films to deliver compounds to a variety of food surfaces, including muscle foods. As mentioned previously, these types of films, gels or coatings are receiving considerable attention since they satisfy consumers' demands for products made from sustainable materials and/or recyclability (Durango et al., 2006).

Numerous researchers have demonstrated that antimicrobial compounds such as organic acids (acetic propionic, benzoic, sorbic, lactic, lauric), potassium sorbate, bacteriocins (nisin, lacticin), grape seed extracts, spice extracts (thymol, *p*-cymene, cinnamaldehyde), thiosulfinates (allicin), enzymes (peroxidase, lysozyme), proteins (conalbumin), isothiocyanates (allylisothiocyanate), antibiotics (imazalil), fungicides (benomyl), chelating agents (EDTA), metals (silver), or parabens (heptylparaben) could be added to edible films to reduce bacteria in solution, on culture media, or on a variety of muscle foods (Cha & Chinnan, 2004; Cutter, 2002a, 2002b; Devlieghere, Vermeiren, Bockstal, & Debevere, 2000; Han, 2000).

Additional studies also have demonstrated that antifungal compounds, organic acids, potassium sorbate, or the bacteriocin nisin, were more effective for reducing levels of foodborne organisms when immobilized or incorporated into an edible film made from starch, carrageenan, or alginate, and applied to meat surfaces than when these antimicrobial compounds were applied via solution (Baron & Sumner, 1994; Cutter & Siragusa, 1996, 1997; Dawson et al., 1996; Meyer et al., 1959; Padgett, Han, & Dawson, 1998; Siragusa & Dickson, 1992, 1993). For example, Meyer et al. (1959) were among the first researchers to demonstrate that antibiotics and antifungal compounds could be added to a carrageenan film to reduce bacteria by $2 \log_{10}$ (99%) on poultry. Antimycotic agents also have been incorporated into edible coatings from waxes and cellulose ethers (Hotchkiss, 1995). Siragusa and Dickson (1992, 1993) demonstrated that organic acids were more efficacious for reducing levels of *L. monocytogenes*, *S. typhimurium*, and *E. coli* O157:H7 when immobilized in calcium alginate and applied to beef carcass tissue than when these materials were applied alone. Baron and Sumner (1994) demonstrated that potassium sorbate and lactic acid could be incorporated into an edible cornstarch film to inhibit *S. typhimurium* and *E. coli* O157:H7 on poultry. Cutter and Siragusa (1996, 1997) reported that immobilization of the bacteriocin nisin in calcium alginate gels not only resulted in greater reductions of bacterial populations on lean and adipose beef surfaces, but also resulted in greater and sustained bacteriocin activity when the tissues were ground and stored under refrigerated conditions for up to 7 days, as compared to nisin-only controls. Fang and Lin (1994) applied calcium alginate containing nisin to pork and also demonstrated significant reductions in pathogen populations.

In other similar studies, Dawson et al. (1996) and Padgett et al. (1998) demonstrated that nisin and lysozyme could be incorporated into edible heat-set and cast films made from corn zein or soy protein and exhibit activity against *E. coli* and *Lactobacillus plantarum*. Hoffman, Han, and Dawson (2001) demonstrated that corn zein films impregnated with EDTA, lauric acid, nisin, and combinations of the three compounds resulted in significant reductions of *Listeria monocytogenes* in solution. Franklin, Cooksey, and Getty (2004) also demonstrated that *L. monocytogenes* could be inhibited $>2\log_{10}$ (99%) on the surface of hot dogs using plastic-based packaging films treated with methylcellulose/hydroxypropyl methylcellulose-based solutions containing nisin.

A number of additional studies have demonstrated that antimicrobial compounds can be incorporated into edible films made from animal-derived proteins (i.e. collagen, gelatin, and chitosan). Gill (2000) applied gelatin-based coatings containing lysozyme, nisin, and EDTA to ham and sausage to control spoilage and pathogenic organisms such as *L. sake*, *Leuconostoc mesenteroides*, *L. monocytogenes*, and *S. typhimurium*. Cutter and Siragusa (1998) demonstrated that the addition of the bacteriocins, nisin, into a bovine-derived fibrinogen/thrombin-based gel, known as Fibrimex®, may provide an added antimicrobial advantage to restructured raw meat products that incorporate surface tissues into product interior or as a delivery system for antimicrobials to meat surfaces. Cutter and Miller (2004) also demonstrated that *Brochothrix thermosphacta* and *L. monocytogenes* were inhibited on hot dog surfaces following treatments with nisin-incorporated collagen (Coffi) films (NICF) subjected to temperature abuse as well as long term refrigerated storage.

Chitosan films have been made following treatments with various acids and incorporated into packaging films for processed meats and seafood, as well as combined with nisin and coated onto the surfaces of paper for inhibiting microorganisms (Vartiainen et al., 2004). Durango et al. (2006) also developed and evaluated an edible film made from 3% or 5% chitosan and yam starch against *S. enteritidis* in suspensions. When applied directly to cell suspensions, 1% chitosan reduced the pathogen $>4\log_{10}$ CFU/ml (or 99.99%). Subsequent experiments demonstrated that chitosan-treated films made with 3% or 5% chitosan reduced populations of *S. enteriditis* $> 1\log_{10}$ CFU/ml (or 90%). The authors demonstrated that chitosan-treated films made with 5% chitosan were the most efficient treatment for inhibiting *S. enteriditis* in solution and that the application of these films to foodstuffs was in progress. In another study Cooksey (2005) incorporated nisin into chitosan to inhibit *L. monocytogenes*. In solution and in agar diffusion assays, the antimicrobial film inhibited the pathogen, but no further studies were conducted in meat systems. And finally, Simpson, Gagné, Ashie, and Noroozi (1997) Chen, Liau, and Tsai (1998) demonstrated that chitosan coatings reduced microbial contamination on shrimp and oysters, respectively.

Another study addressed the application of antimicrobials with milk proteins for edible films and coatings for foods. Whey protein films were treated with essential oils of oregano, rosemary, and garlic and evaluated against *E. coli* O157:H7, *S. aureus*, *S. enteriditis*, *L. monocytogenes*, and *L. plantarum* (Seydim, 2006). While these studies demonstrated efficacy of the antimicrobial compound *in vitro*, additional studies with surface-inoculated foodstuffs are warranted.

A number of additional studies have addressed the production of edible films from agricultural other sources and the interaction with antimicrobials. For example, pullulan films can be produced by fungi during fermentation. In a recent study, lysozyme and disodium EDTA were incorporated into pullulan films made from the exopolysaccharides of *Aureobasidium pulluans* and evaluated for antimicrobial effectiveness against *E. coli* and *L. plantarum* (Kandemir et al., 2005). The resulting films were composed of glucans and polysaccharides, were a neutral pH, water soluble, transparent, and exhibited low oxygen permeability (Kandemir et al., 2005). In their studies, the researchers demonstrated that these antimicrobial films were stable for up to 21 days during cold storage and could inhibit the *E. coli* under laboratory conditions (Kandemir et al., 2005). Further research will investigate the application of these films to food products.

As evidenced by the information presented above, the application of biopolymers, bio-based polymers, edible gels, films, or coatings incorporated with food preservatives and/or natural antimicrobial compounds have the potential to find practical applications in the food industry. This specific information demonstrates the feasibility and applicability for incorporating various antimicrobial compounds with a range of inhibitory activity directly into bio-based or edible packaging materials for use in controlling food spoilage as well as enhancing microbial safety of muscle foods.

7. Conclusions

Consumer demands are driving research and development for alternatives to petroleum-based packaging materials including those with recyclable or edible properties, as well as those materials made from renewable/sustainable agricultural products. Edible films, gels or coatings are considered biopolymers with numerous desirable properties and may be made from a variety of materials including polysaccharides, lipids, proteins, alone or in combination with other components. Biopolymers also have been developed from other sources and applied to muscle foods, including fungal exopolysaccharides (pullan) or fermentation by-products (polylactic acid). When applied to muscle foods with other food grade compounds (i.e. chelators, antimicrobials, anti-oxidants), bio-based, edible, or biopolymer packaging cannot only enhance the quality or safety of the food, but slow deterioration, extend the shelf life, and in some cases, impart desirable characteristics (color, flavor, etc.) to the food. However, as with all new or novel packaging developments destined for consumers, cost, organoleptic, consumer preference, toxicological, safety, and regulatory considerations must be addressed if these types of technologies are to be adopted and implemented by the muscle foods industry (Cutter, 2002b).

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