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Innovations in the Development and Application of Edible Coatings for Fresh and Minimally Processed Fruits and Vegetables

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ABSTRACT: One of the major growth segments in the food retail industry is fresh and minimally processed fruits and vegetables. This new market trend has thus increased the demands to the food industry for seeking new strategies to increase storability and shelf life and to enhance microbial safety of fresh produce. The technology of edible coatings has been considered as one of the potential approaches for meeting this demand. Edible coatings from renewable sources, including lipids, polysaccharides, and proteins, can function as barriers to water vapor, gases, and other solutes and also as carriers of many functional ingredients, such as antimicrobial and antioxidant agents, thus enhancing quality and extending shelf life of fresh and minimally processed fruits and vegetables. This review discusses the rationale of using edible coatings on fresh and minimally processed produce, the challenges in developing effective coatings that meet the specific criteria of fruits and vegetables, the recent advances in the development of coating technology, the analytical techniques for measuring some important coating functionalities, and future research needs for supporting a broad range of commercial applications.

Introduction

Fruits and vegetables remain as living tissues up until the time they are consumed fresh, cooked for consumption, or processed for preservation. Controlling respiration of these living tissues would improve storability and extend shelf life of fresh produce a certain level of respiration activity is required to prevent plant tissues from senescing and dying. Minimally processed produce such as fresh-cut fruits and vegetables are essentially wounded tissues, leading directly to tissue softening and browning discoloration on cut surfaces. The intensity of the wound response is affected by a number of factors, including species and variety, O_2 and CO_2 concentrations, water vapor pressure, and the presence of inhibitors (Brecht and others 2004). The concept of using edible coatings to extend shelf life of fresh and minimally processed produce and protect them from harmful environmental effects has been emphasized based on the need for high quality and the demand for minimal food processing and storage technologies. By regulating the transfer of moisture, oxygen, carbon dioxide, aroma, and taste compounds in a food system, edible coatings have demonstrated the capability of improving food quality and prolonging shelf life of fresh produce. Edible coatings may also be used to advantage on processed fruits and vegetables for improving structural integrity of frozen fruits and vegetables and preventing moisture absorption and oxidation of freeze-dried fruits or vegetables (Baker and others 1994; Baldwin and Baker 2002; Olivas and Barbosa-Vanovas 2005; Park 2005). In addition, edible coatings can carry functional ingredients such as antioxidants, antimicrobials, nutrients, and flavors to further enhance food stability, quality, functionality, and safety (Krochta and others 1994; Krochta and De Mulder-Johnson 1997; Debeaufort and others 1998; Min and Krochta 2005).

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Quality Attributes of Fresh and Minimally Processed Fruits and Vegetables

The most important quality attributes contributing to the marketability of fresh and minimally processed produce include appearance, color, texture, flavor, nutritional value, and microbial safety (Table 1). These quality attributes are determined by plant variety, stage of maturity or ripening, and the pre- and postharvest conditions; and all can change rapidly during postharvest storage.

Appearance

Appearance is the most important quality attribute of fresh and minimally processed produce, with primary concern for size and color uniformity, glossiness, and absence of defects in shape or skin finish (Aked 2000). Many fruits and vegetables undergo color changes as part of the ripening process. Color is of special importance in fresh-cut fruits and vegetables, since oxidation and enzymatic browning take place quickly upon contact with oxygen, leading to discoloration. Other aspects of appearance include inconsistent size and dimension, wilting, loss of surface gloss, skin wrinkling, and skin blemishes caused by natural senescence or the growth of microorganisms (Kader 1985a).

Texture

The texture of fruits and vegetables is often interpreted in terms of firmness, crispness, juiciness, and toughness (attributed by the fibrousness of plant tissue), where firm or crispy tissues are generally desired in fresh and minimally processed produce. Texture is an important quality indicator for eating and cooking, and a factor in withstanding shipping stresses. However, the development of tough fibers in stem crops, such as asparagus, or toughness caused by dehydration of fresh produce is unacceptable. Losses in juiciness often result in dry and tough structures that lead to adverse effects on quality.

Flavor

Flavor involves perception of many taste and aroma components (Kader 2002). Common taste components in fresh produce are sweetness, acidity, astringency, and bitterness. The sugar level of fruits often determines whether the item has reached the required ripeness for marketing. Acid level is critical to the flavor balance of certain fruits, such as citrus species and grapes, and generally decreases during ripening and postharvest storage. Bitterness and astringency can develop in various fruits and vegetables under certain storage conditions. The aroma profile can change dramatically during the postharvest life of fresh produce, particularly in climacteric fruits, in which the dominant volatile may vary significantly based on maturity of the fruit. Coldness also tends to limit the development of aroma volatiles in ripening fruits.

Table 1 — Major quality attributes of fresh fruits and vegetables

Quality factor	Primary concerns
Appearance (visual)	Size Shape and form Color: intensity, uniformity Gloss Defects
Texture (mouth-feel)	Firmness/softness Crispness Juiciness Toughness (fibrousness)
Flavor (taste, aroma)	Sweetness Acidity Astringency Bitterness Volatile compounds
Nutritional value	Vitamins Minerals
Safety	Toxic substances Chemical contaminants Microbial contamination

Nutritional quality

Fresh fruits and vegetables are important source of nutrients, including vitamins (B6, C, thiamin, niacin), minerals, dietary fibers, and significant amounts of phytochemicals that play important roles in human health. Postharvest losses in nutritional quality, particularly vitamin C content and some phytochemicals, can be substantial. The losses can be increased in minimally processed fruits and vegetables.

Safety

Safety factors include naturally occurring toxicants, contaminants such as chemical residues and heavy metals, and microbial contamination. Fresh produce items are highly susceptible to fungal spoilage. Contamination by pathogenic or spoilage microorganisms is especially important for minimally processed fruits and vegetables. Proper sanitation and handling procedures can help reduce the potential risk of contaminations.

Preharvest Factors

There are numerous preharvest factors affecting the postharvest quality and life of fruits and vegetables, including harvest maturity, cultivar or variety, climate, and soil in which the produce grew, chemicals applied, and water status (Thompson 2003a). Within each commodity there is a range of genotypic variation in composition, quality, and postharvest life (Kader 2002). The soil type and its fertility also affect the chemical composition of a produce. In some cases, the mineral content of fruits, such as phosphorus (Knowles and others 2001), potassium (Cirulli and Ciccarese 1981; Chiesa and others 1998), and calcium (Yuen 1993; Rabus and Streif 2000), can be used to predict postharvest quality. Rootstocks used in fruit production vary in their water and nutrient uptake abilities and in resistance to pests and diseases, and thus have a profound effect on the postharvest life of the produce (Tomala and others 1999). Climate factors, especially light intensity and temperature, have strong influences on the composition and nutritional quality of fruits and vegetables. Those constantly exposed to the sun may have different quality and postharvest characteristics from those growing on the shady side (Oosthuyse 1998; Ferguson and others 1999).

Postharvest Factors

Fruits and vegetables undergo many physiological changes during postharvest storage, including tissue softening, increase in sugar level, and decrease in organic acid levels, degradation of chlorophyll accompanied by the synthesis of anthocyanins or carotenoids upon maturation, production and losses of volatile flavor compounds, decrease in phenolic and amino acid contents, and breakdown of cell materials due to respiration (Sharma and Singh 2000) (Table 2).

Harvesting practices determine the extent of variability in maturity and physical injuries. Physical injuries lead to accelerated loss of water and vitamin C and increased susceptibility to decay by fungi or pathogens during storage (Sharma and Singh 2000; Kader

2002). Temperature and relatively humidity (RH) directly affect postharvest respiration and transpiration of fruits and vegetables. Elevated temperature would speed up respiration, leading to increased ethylene production and high carbon dioxide level (Kader 1985b), and thus changes in flavor, taste, color, texture, appearance, and nutrients of the produce. Appropriate postharvest handling operations should be applied, including controlling temperature (cooling) and RH, atmosphere (O_2 and CO_2 levels), cleaning, waxing, and packaging applications (Sharma and Singh 2000; Kader 2002). Temperature of fresh produce should be reduced immediately after harvesting and controlled right above where the chilling injury may occur (Thompson 1996). Modified atmospheric (MA) environments with reduced O_2 and increased CO_2 levels up to 10% have shown reduced ascorbic acid loss and extended postharvest life of many different varieties of fruits and vegetables (Kader 2002). However, the responses to MA environment vary greatly among plant species, maturity stage, and duration and temperature of exposure. Ethylene usually promotes the ripening process of fruits and vegetable. Exposure of fruits and vegetables to unwanted ethylene should be avoided by separating ethylene-producing commodities from ethylene-sensitive commodities, by using ethylene scrubbers, or by introducing fresh air into storage rooms.

Table 2—Major factors affecting quality and shelf life of postharvest fruits and vegetables

Physical factors contributing to postharvest quality losses

1. Loss of moisture, causing wilting and/or shrinkage
2. Loss of stored energy (such as carbohydrates)
3. Loss of other food constituents (such as vitamins)
4. Pests and disease attacks
5. Loss in quality from physiological disorders
6. Fiber development
7. Greening (potatoes)
8. Root or shoot growth
9. Seed germination

Spoilage of fresh produce

1. Growth and activity of microorganisms/pathogens; succession of organisms
2. Insects, rodents
3. Improper action/damage to plant enzymes
4. Physical changes resulting such as from freezing, burning, drying, pressure, and so on

Fruits and vegetables are susceptible to spoilage by microorganisms. Postharvest spoilage was estimated to be about one-fourth of all produce harvested (Salunkhe 1974; Salunkhe and Kadam 1998). The survival and growth of pathogenic microorganisms are the major food safety concerns in fresh and minimally processed fruits and vegetables due to possible contamination during preparation and increased nutrients and cellular fluid on the fresh-cut surface. Implementation of appropriate postharvest sanitation operation procedures during preparation and processing and maintenance of product in refrigerated and sanitized condition is essential for controlling microbial growth, thus providing high-quality and safe products.

Use of Edible Coatings for Fresh and Minimally Processed Fruits and Vegetables

Edible coatings have long been used to retain quality and extend shelf life of some fresh fruits and vegetables, such as citric fruits, apples, and cucumbers (Baldwin and others 1996; Li and Barth 1998). Fruits or vegetables are usually coated by dipping in or spraying with a range of edible materials, so that a semipermeable membrane is formed on the surface for suppressing respiration, controlling moisture loss, and providing other functions (Ukai and others 1976; Thompson 2003b). A variety of edible materials, including lipids, polysaccharides, and proteins, alone or in combinations, have been formulated to produce edible coatings (Ukai and others 1976; Kester and Fennema 1986). Lipid-based coatings made of acetylated monoglycerides (AM), waxes (beeswax, carnauba, candelilla, paraffin, and rice bran), and surfactants were the 1st successful ones on whole fruits and vegetables (Paredes-Lopez and others 1974; Lawrence and Iyengar 1983; Warth 1986), used for reducing surface abrasion during handling and serving as moisture barrier (Hardenburg 1967). Colloidal suspensions of oils or waxes dispersed in water were typical early fruit-coating formulations.

Appropriately formulated edible coatings can be utilized for most foods to meet challenges associated with stable quality, market safety, nutritional value, and economic production cost. With regard to the fresh produce industry, the potential benefits of using edible coatings include (Figure 1):

1. To provide moisture barrier on the surface of produce for helping alleviate the problem of moisture loss. Moisture loss during postharvest storage of fresh produce leads to weight loss and changes in texture, flavor, and appearance.

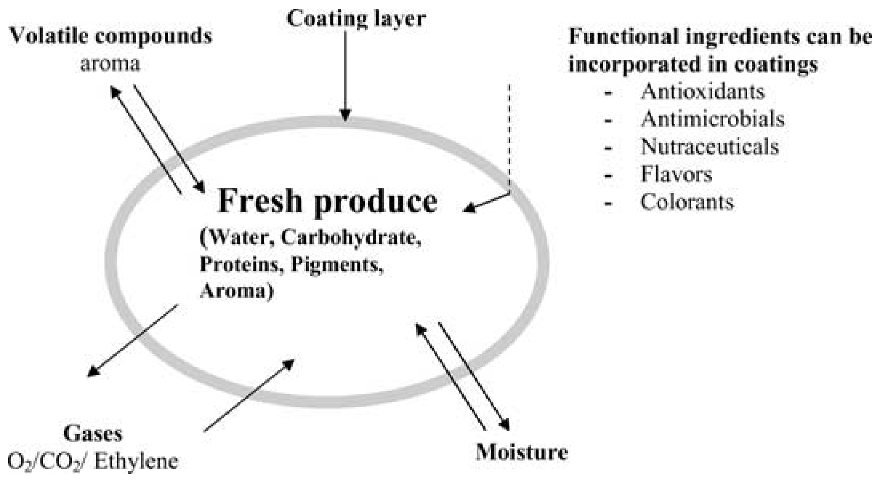

Figure 1—Functional properties of an edible coating on fresh fruits and vegetables

2. To provide sufficient gas barrier for controlling gas exchange between the fresh produce and its surrounding atmosphere, which would slow down respiration and delay deterioration. The gas-barrier function could in turn retard the enzymatic oxidation and protect the fresh produce from browning discoloration and texture softening during storage.

3. To restrict the exchange of volatile compounds between the fresh produce and its surrounding environment through providing gas barriers, which prevents the loss of natural volatile flavor compounds and color components from fresh produce and the acquisition of foreign odors.

4. To protect from physical damage of produce caused by mechanical impact, pressure, vibrations, and other mechanical factors.

5. To act as carriers of other functional ingredients, such as antimicrobial and antioxidant agents, nutraceuticals, and color and flavor ingredients for reducing microbial loads, delaying oxidation and discoloration, and improving quality (Rooney 2005).

Challenges in Developing Edible Coatings for Fruits and Vegetables

The success of an edible coating for meeting the specific needs of fresh and minimally processed fruits and vegetables strongly depends on its barrier property to moisture, oxygen, and carbon dioxide, which in turn depends on the chemical composition and structure of the coating-forming polymers, the characteristics of the produce, and the storage conditions. Several edible coatings, including cellulose, casein, zein, soy protein, and chitosan, have shown such desirable characteristics on fresh produce: good barrier properties, odorless, tasteless, and transparent. However, commercial success is still limited. Challenges in the edible coatings targeted for fruits and vegetables may include:

1. limited moisture-barrier properties of the hydrophilic nature of most edible coating materials;
2. variable oxygen and carbon dioxide-barrier properties due to poor temperature and relative humidity control in the storage, transportation, and marketing of fruits and vegetables;
3. unfavorable storage environment induced by improper gas-barrier property of some coating materials;
4. inefficient coating coverage and poor coating adhesion between coating layer and the surface of fruits and vegetables; and
5. adverse sensory effect from exogenous flavor imparted by some of the coating materials.

As discussed in the previous sections, major quality deteriorations involved in fresh produce are via mass transfer phenomena, including moisture adsorption, oxygen invasion, flavor loss, undesirable odor absorption, and the migration of packaging components into the food (Kester and Fennema 1986; Debeaufort and others 1998; Miller and others 1998; Krochta 2002). Hence, permeation, absorption, and diffusion into water, oxygen, and carbon dioxide are among the most important functional properties of any edible coating applied to fruits and vegetables.

Table 3 shows the water vapor, oxygen, and carbon dioxide permeability values of some edible coating materials when made into films. Most polysaccharide-based and protein-based materials are hydrophilic and are not satisfactory in some cases for controlling the moisture loss of high-moisture foods unless other hydrophobic compounds are integrated into the film formulations. On the other hand, hydrophobic coating materials, such as sucrose polyesters, provide relatively better moisture barriers than hydrophilic materials (Table 3). In order to extend the shelf life of fresh produce, coating materials and formulations must be carefully selected and designed.

Gas-barrier properties of the coatings, including oxygen, carbon dioxide, ethylene, and volatiles, are necessary for slowing down respiration of fresh produce and preventing exchange of food aroma and flavor compounds with the environment. Coatings are used to create a controlled or modified atmosphere inside the fruits and vegetables that will delay ripening and senescence in a manner similar to the more costly controlled or modified atmosphere storage. However, the modification of internal atmosphere by the use of edible coatings can develop ethanol and alcoholic flavors as a result of anaerobic fermentation associated with too high carbon dioxide or too low oxygen concentrations (Smock 1940; Ben-Yehoshua 1969). Selecting a coating material with appropriate permeability for various gases is critical in modifying the internal environment of fresh produce for the purpose of preserving food. In addition, controlling environmental temperature and relatively humidity is also critical in modifying the internal environment of fresh produce since coating

Table 3—Comparison of permeability (at 25 ± 2 °C, 50% to 70% RH) of some synthetic polymers with edible films/coatings[a]

		Permeability	
Film/coating material	**O_2 ($m^3.m/m^2.s.Pa$)**	**CO_2 ($m^3.m/m^2.s.Pa$)**	**H_2O vapor ($g.m/m^2.s.Pa$)**
Synthetic polymer			
Polyester	2.69×10^{-19}	2.61×10^{-17}	3.6×10^{-13}
Polypropylene (PP)	5.5×10^{-17}	—	6.5×10^{-13}
Polyvinyl chloride (PVC)	5.15×10^{-19}	$1.35 \times 10^{-18} - 2.7 \times 10^{-17}$	2.16×10^{-11}
Polyethylene terephthalate (PET)	2.15×10^{-19}	$6.7 \times 10^{-19} - 1.12 \times 10^{-18}$	—
Low-density polyethylene (LDPE)	2.25×10^{-17}	—	8.1×10^{-13}
High-density polyethylene (HDPE)	5.02×10^{-18}	—	2.52×10^{-13}
Edible coating material			
Methylcellulose (MC)	3.85×10^{-6}	6.9×10^{-5}	9.35×10^{-11}
Hydroxypropyl cellulose (HPC)	3.1×10^{-6}	1.13×10^{-4}	5.55×10^{-7}
Sucrose polyester	2.10×10^{-18}	—	4.2×10^{-13}
Zein	7.84×10^{-19}	2.67×10^{18}	1.17×10^{-10}
Chitosan	1.4×10^{-21}	—	4.9×10^{-10}
Wheat gluten	2.89×10^{-17}	2.13×10^{-18}	9.18×10^{-11}
Whey protein isolate (WPI)	1.13×10^{-18}	—	1.1×10^{-9}
Soy protein	3.14×10^{-19}	—	3.49×10^{-10}

[a] Data presented in the table are summarized from Miller and Krochta (1997) and Park (1999).

permeability and produce respiration are both affected by these parameters.

For fully taking advantages of edible coatings, the coating must adhere to the food surface. Wax-based coatings have shown good adhesion on whole fruits, including oranges, grapefruits, lemons, apples, and pears (Hoffman 1916; Baldwin and others 1997; Min and Krochta 2005). However, adhesions of most hydrophilic edible coatings on the hydrophobic whole fruit surface are inherently poor due to the different chemical nature of the 2 surfaces. For improving surface adhesion of hydrophilic coatings, surfactants are typically added into coating formulations to improve wettability and adhesion of the coatings (Choi and others 2002; Lin and Krochta 2005). When applying a coating onto the fresh-cut fruit or vegetable surfaces covered with juice, it presents an even more considerable challenge, because coatings may be dissolved and absorbed by the wet surfaces instead of drying to form a smooth and unique layer.

One potential adverse effect of the use of edible coating is the development of undesirable sensory properties on the coated products. Off-flavors may occur due to the existing flavor of coating materials or as the result of anaerobic respiration from excess inhibition of O_2 and CO_2 exchange. In addition, nonuniform and/or sticky surfaces may appear, making the product unattractive to consumers (Zhao and McDaniel 2005). Some of the important sensory attributes that should be considered when developing an edible coating for fresh and minimally processed produce include (Zhao and McDaniel 2005):

1. Appearance as a result of surface dehydration, whitening, waxiness, and discoloration (as due to enzymatic browning). Selective coating materials can reduce moisture loss, control surface dehydration and discoloration, delay the surface whitening, and enhance the glossiness of food surfaces.
2. Texture as mostly represented by firmness and crispness. Texture of the produce can be improved by edible coatings through reducing water loss and preventing dehydration. In addition, edible coatings may improve the mechanical integrity or handling characteristic of food products.
3. Flavor and other sensory attributes. Edible coating can retard ethylene production and delay the ripening process, thus preventing the development of off-flavor and off-taste during postharvest storage of the produce. The ingredients used for edible coating formation (such as film-forming material, plasticizer) should be carefully selected to avoid undesirable flavors and tastes.

Edible Coating Materials for Fruits and Vegetables

Most fruits and vegetables possess a natural waxy layer on the surface, called cuticle. This waxy layer generally has a low permeability to water vapor. Applying an external coating will enhance this natural barrier or replace it in cases where this layer has been partially removed or altered during postharvest handling or processing. Coatings provide a partial barrier to moisture and gas exchange, improve the mechanical handling property through helping maintain structural integrity, retain volatile flavor compounds, and carry other functional food ingredients.

Biopolymers such as proteins, polysaccharides, lipids, and resins are the common coating-forming materials that can be used alone or in combinations. The physical and chemical characteristics of the biopolymers greatly influence the functionality of resulting coatings (Sothornvit and Krochta 2000). Selection of coating materials is generally based on their water solubility, hydrophilic and hydrophobic nature, easy formation of coatings, and sensory properties. This section discusses the coating materials feasible for fruit and vegetable applications, and the innovations in this application. Table 4 summarizes the recent reports on using edible coatings for fresh and minimally processed fruits and vegetables.

Lipid-based coatings

Lipid compounds include neutral lipids of glycerides which are esters of glycerol and fatty acids and the waxes which are esters of long-chain monohydric alcohols and fatty acids, while resins are a group of acidic substances that are usually secreted by special plant cells into long resin ducts or canals in response to injury or infection in many trees and shrubs (Hernandez 1994). Edible lipids including neutral lipids, fatty acids, waxes, and resins are the traditional coating materials for fresh produce, showing the effectiveness in providing moisture barrier and improving surface appearance (Kester and Fennema 1986; Hernandez 1994; Hagenmaier and Baker 1994, 1995; Morillon and others 2002). Very comprehensive reviews on the applications of different types of lipid-based coatings for fruits and vegetables have been done by Hernandez (1994), Baldwin (1994), Baldwin and others (1997), and Min and Krochta (2005).

Waxes (carnauba wax, beeswax, paraffin wax, and others) have been commercially applied as protective coatings for fresh whole fruits and vegetables since the 1930s with the purpose of blocking moisture transport, reducing surface abrasion during fruit handling (Lawrence and Iyengar 1983; Warth 1986), and controlling soft scald formation (browning of the skin) in fruits such as apples by improving mechanical integrity and controlling internal gas composition of the fruits (Kester and Fennema 1986). In general, wax coatings are substantially more resistant to moisture transport than other lipid or nonlipid coatings (Schultz and others 1949; Landmann and others 1960; Watters and Brekke 1961; Kaplan 1986). Commercial applications of wax coatings is rather extensive on citrus, apples, mature green tomatoes, rutabagas, cucumbers, and other vegetables such as asparagus, beans, beets, carrots, celery, eggplant, kohlrabi, okra, parsnips, peppers, potatoes, radishes, squash, sweet potatoes, and turnips (Hardenburg 1967), where high glossing and shine surface are desired. Waxes-based coatings are continuously evaluated for their applications in citric fruits, melons, and some tree fruits such as apples and pears (Mannheim and Soffer 1996; Hagenmaier and Baker 1997; Petracek and others 1998; Alleyne and Hagenmaier 2000; Hagenmaier 2000; Bai and others 2002, 2003b; Da-Mota and others 2003; Fallik and others 2005; Porat and others 2005).

Shellac and other resin-based coatings generally have lower permeability to O_2, CO_2, and ethylene gas, and shellac coatings also dry fast and produce a shiny surface on coated produce (Baldwin 1994). Resin coatings are fairly effective at reducing water loss, but are least permeable to gases among the available coating film-formers, meaning that fruit can easily undergo anaerobic respiration and flavor changes that are usually undesirable. Some climatic fruit do not tolerate resin coatings at all due to impaired ripening from the MA created by these materials (Baldwin and Baker 2002; Porat and others 2005). The gas permeability of shellac and several experimental coating formulations, including candelilla wax and shellac carnauba, was measured by Bai and others (2003b) on different varieties of apples. It was found that the shellac coating resulted in maximum fruit gloss, lowest internal O_2, highest CO_2, and least loss of flesh firmness for all of the apple varieties. However, the shellac coating gave an unusual accumulation of ethanol in freshly harvested and 5-mo-stored ‘Fuji,’ candelilla and carnauba-shellac coatings maintained more optimal internal O_2 and CO_2 and better quality for ‘Fuji,’ ‘Braeburn,’ and ‘Granny Smith’ apples, although even these coatings may present too much of a gas barrier for ‘Granny Smith.’ It was recommended the best coatings as shellac for ‘Delicious,’ and carnauba-shellac for ‘Braeburn’ or ‘Fuji’ (Bai and others 2003b).

Triglycerides or neutral lipids can form a continuous stable layer on the food surface based on their high polarity relative to waxes. Most fatty acids derived from vegetable oils are considered GRAS (generally recognized as safety) substances and have been suggested as substitutes for the petroleum-based mineral oils used in the preparation of edible coatings (Hernandez 1994; Baldwin and others 1997). However, these coatings may suffer from flavor instability, while partially hydrogenated vegetable oil that is resistant to rancidity sometimes gives better results (Kochhar and Rossell 1982).

The beneficial properties of lipid-based coating, including waxes-, resins-, neutral lipids-, and fatty acid-based coatings, include good compatibility with other coating-forming agents and high water vapor and gas-barrier properties in comparison with polysaccharides- and protein-based coatings (Greener and Fennema 1992). However, lipid-based coatings present a greasy surface and undesirable organoleptic properties such as waxy taste and lipid rancidity (Guilbert 1986). Waxes and shellac tend to restrict the gas exchange of O_2 and CO_2 between atmosphere and fruit to the extent that the internal O_2 level becomes too low to support aerobic respiration, resulting in high levels of internal ethanol, acetaldehyde, and internal CO_2 (Petracek and others 1998; Alleyne and Hagenmaier 2000). This leads to accumulation of off-flavors in the fruit (Mannheim and Soffer 1996; Baldwin and

Table 4—Examples of edible coating applications on fruits and vegetables that have been investigated

Commodity	Coating material	Primary functions	References
Apple	Caseinate; whey protein	O_2 barrier; carrier (antioxidant)	Le Tien and others (2001)
Apple (fresh-cut)	HPMC	O_2/H_2O barrier	Cisneros-Zevallos and Krochta (2003)
	Alginate; gelatin, CMC	$O_2/CO_2/H_2O$ barrier	Moldão-Martins and others (2003)
	Polysaccharide/lipid bilayer	O_2/CO_2 barrier, gloss	Wong and others (1994a, 1994b)
	Zein	$O_2/CO_2/H_2O$ barrier, gloss	Bai and others (2003a)
	Wax; shellac	O_2/CO_2 barrier	Bai and others (2003b)
	Carrageenan; WPC	O_2/H_2O barrier	Lee and others (2003)
	WPI-BW emulsion	O_2 barrier	Perez-Gago and others (2003b)
	WPI; WPC, HPMC; wax		Perez-Gago and others (2005)
Avocado	Methylcellulose	$O_2/CO_2/H_2O$ barrier	Maftoonazad and Ramaswamy (2005)
Carrot (peeled)	Xanthan gum	H_2O barrier; Ca^{2+}, Vit. E carrier	Mei and others (2002)
	Calcium caseinate; WPI; pectin; CMC	H_2O barrier	Lafortune and others (2005)
	Alginate	H_2O barrier; microbial barrier	Amanatidou and others (2000)
Celery	Caseinate	$O_2/CO_2/H_2O$ barrier; carrier (antimicrobial)	Avena-Bustillos and others (1997)
Cherry	Semperfresh^{TM}	O_2/H_2O barrier	Yaman and Bayoindirli (2002)
	Caseinate; milk protein	$O_2/CO_2/H_2O$ barrier	Certel and others (2004)
Corn	Zein	Microbial barrier	Carlin and others (2001)
Green bell pepper	Lipid-based	$O_2/CO_2/H_2O$ barrier	Conforti and Ball (2002) Conforti and Zinck (2002)
Kiwifruit	Pullulan (bacterial polysaccharide from starch)	$O_2/CO_2/H_2O$ barrier	Diab and others (2001)
Lettuce	Alginate-based	O_2/CO_2 barrier	Tay and Perera (2004)
Litchi fruit (peeled)	Chitosan	O_2/H_2O barrier	Dong and others (2004)
	Chitosan	O_2 barrier	Jiang and others (2005)
Mango fruit	Wax; shellac; zein; cellulose derivative	$O_2/CO_2/H_2O$ barrier	Hoa and others (2002)
Mushroom	Alginate	O_2/H_2O barrier	Hershko and Nussinovitch (1998)
Citrus	Chitosan	$O_2/CO_2/H_2O$ barrier	Fornes and others (2005)
Peach	Wax; CMC	H_2O barrier	Toğrul and Arslan (2004)
Pear (cut wedges)	Methylcellulose-based	$O_2/CO_2/H_2O$ barrier, carrier (antioxidant)	Guadalupe and others (2003)
	Methylcellulose	$O_2/CO_2/H_2O$ barrier	Olivas and others (2003)
Plum	HPMC/lipid composite	$O_2/CO_2/H_2O$ barrier	Perez-Gago and others (2003a)
Potato	Caseinate; whey protein	O_2 barrier; carrier (antioxidant)	Le Tien and others (2001)
Quince	Semperfresh^{TM}	$O_2/CO_2/H_2O$ barrier	Yurdugül (2005)
Raspberry	Chitosan	H_2O barrier; Ca^{2+}, Vit. E carrier	Han and others (2004b)
Strawberry	Cactus mucilage	O_2 barrier	Del-Valle and others (2005)
	Caseinate-whey protein	microbial barrier	Vachon and others (2003)
	Chitosan	H_2O barrier; Ca^{2+}, Vit. E carrier	Han and others (2004a, 2004b)
	Chitosan; HPMC	H_2O barrier; carrier (antimicrobial)	Park and others (2005)
	Pullulan (bacterial polysaccharide from starch)	$O_2/CO_2/H_2O$ barrier	Diab and others (2001)
	Starch-based	H_2O barrier, carrier (antimicrobial)	Garcia and others (1998)
	Wheat gluten-based	O_2/H_2O barrier	Tanada-Palmu and Grosso (2005)
Water chestnut (fresh-cut)	Chitosan	O_2 barrier	Pen and Jiang (2003)
Zucchini	Semperfresh^{TM}	$O_2/CO_2/H_2O$ barrier	Kaynas and Ozelkok (1999)

others 1997; Hagenmaier 2002). In addition, some lipid materials, such as shellac, are unstable when subjected to temperature changes, where a white waxy layer usually appears when moving fruits from cold storage to the grocery display shelves due to temperature fluctuation. Currently, lipid-based coating materials are usually studied in combination with polysaccharide- or protein-based coating materials for forming composite coatings, taking advantages of the desirable properties of different materials. A more detailed discussion on the composite coatings appears in a later section.

Polysaccharide-based coatings

Polysaccharides that have been evaluated or used for forming films and coatings include starch and starch derivatives, cellulose derivatives, alginates, carrageenan, various plant and microbial gums, chitosan, and pectinates; they were reviewed by Nisperos-Carriedo (1994), Krochta and Mulder-Johnston (1997), and Debeaufort and others (1998). These coatings can be utilized to modify the internal atmosphere, thereby reducing respiration of fruits and vegetables (Banks 1984; Drake and others 1987; Motlagh and Quantick 1988; Nisperos-Carriedo and Baldwin 1990). Due to the hydrophilic nature of polysaccharides, the advantages of using these materials are more apparent as a gas barrier rather than retarding water loss. However, certain polysaccharides, applied in the form of high-moisture gelatinous coatings, can effectively retard moisture loss of food by functioning as sacrificing agents rather than moisture barriers (Kester and Fennema 1986).

Starch and derivatives. Starch, the reserve polysaccharide of most plants, is one of the most abundant natural polysaccharides used as food hydrocolloid (Whistler and Paschall 1965; Narayan 1994) because of its wide range of functionality and relative low cost. Starch films are often transparent (Lourdin and others 1997; Myllärinen and others 2002) or translucent (Rindlav and others 1997), odorless, tasteless, and colorless, and have low permeability to oxygen at low-to-intermediate RH (Mark and others 1966; Roth and Mehltretter 1970). Starch films have low oxygen permeability comparable to ethylene vinyl alcohol copolymer (EVOH), a commercial synthetic oxygen-barrier film, at ambient environment (such as 20 °C, 50% to 60% RH) (Forssell and others 2002), but the oxygen permeability is greatly affected by the water content of the films (Gaudin and others 2000; Forssell and others 2002).

Dextrins, derived from starch with smaller molecular size, are often used as film-formers and edible adhesives (Smith 1984). Coatings from dextrins provided a better water vapor resistance than starch coatings (Allen and others 1963). Pullulan is an extracellular microbial polysaccharide from starch that is edible and biodegradable. Pullulan films cast from aqueous solution are clear, odorless, and tasteless, and have good oxygen-barrier properties too (Yuen 1974; Conca and Yang 1993). Pullulan-based coatings have shown potential for preserving fresh strawberries and kiwifruits because of their barriers to moisture, O_2, and CO_2 (Diab and others 2001). In general, due to its good oxygen barrier, starch is a good candidate for coating fruits and vegetables having high respiration rates, thus suppressing respiration and retarding oxidation of coated products.

Cellulose and derivatives. Cellulose is the structural material of plant cell walls (Nisperos-Carriedo 1994). For producing films, cellulose is first dissolved in an aggressively toxic mixture of sodium hydroxide and carbon disulfide and then recast into sulfuric acid to produce cellophane (Petersen and others 1999). Cellulose ethers are polymer substances obtained by partial substitution of hydroxyl groups in cellulose by ether functions (Felcht 1985). In general, cellulose derivatives possess excellent film-forming property, but are too expensive for large-scale commercial usage. The most common commercially produced cellulose derivatives are carboxymethyl cellulose (CMC), methyl cellulose (MC), hydroxypropyl cellulose (HPC), and hydroxypropylmethyl cellulose (HPMC). These materials are nonionic and compatible with surfactants, other water-soluble polysaccharides, and salt (Nisperos-Carriedo 1994), and can be dissolved in aqueous or aqueous-ethanol solutions, producing films that are water-soluble and resistant to fats and oils (Krumel and Lindsay 1976; Nelson and Fennema 1991; Gennadios and others 1997).

CMC is by far the most important cellulose derivative for food applications (Sanderson 1981). Edible coatings made of CMC, MC, HPC, and HPMC have been applied to some fruits and vegetables for providing barriers to oxygen, oil, or moisture transfer (Morgan 1971; Sacharow 1972; Krumel and Lindsay 1976; Maftoonazad and Ramaswamy 2005), and for improving batter adhesion (Meyers 1990; Dziezak 1991). CMC coatings have shown the capabilities for helping retain the original firmness and crispness of apples, berries, peaches, celery, lettuce, and carrots when used in a dry coating process (Mason 1969), preserving important flavor components of some fresh fruits and vegetables (Nisperos-Carriedo and Baldwin 1990), and reducing oxygen uptake without increasing carbon dioxide level in the internal environment of coated apples and pears by simulating a controlled atmosphere environment (Lowings and Cutts 1982; Banks 1985; Meheriuk and Lau 1988; Santerre and others 1989).

Seaweed extracts. Alginates are the major structural polysaccharides of brown seaweed known as Phaeophyceae (Whistler and BeMiller 1973; Sanderson 1981). Alginates possess good film-forming property, producing uniform, transparent, and water-soluble films. Alginate-based films are impervious to oils and fats but, as other hydrophilic polysaccharides, have high water vapor permeability (Cottrell and Kovacks 1980; King 1983). However, alginate gel coating can act as a sacrificing agent, where moisture is lost from the coating before the food significantly dehydrates (Kester and Fennema 1986). The coating can also improve the adhesion of batter to the surface of fruits and vegetables (Fisher and Wong 1972). Alginate coatings are good oxygen barriers (Conca and Yang 1993) that can retard lipid oxidation in various fruits and vegetables (Kester and Fennema 1986), and have been found to reduce weight loss and natural microflora counts in minimally processed carrots (Amanatidou and others 2000). Calcium-alginate coatings were found to improve the quality of fruits and vegetables, such as reducing shrinkage, oxidative rancidity, moisture migration, oil absorption, and sealing-in volatile flavors, improving appearance and color, and reducing weight loss of fresh mushrooms in comparison with uncoated ones (Hershko and Nussinovitch 1998).

Carrageenan, extracted from several red seaweeds, mainly *Chondrus crispus* (Whistler and Daniel 1985) and a complex mixture of several polysaccharides, is another potential coating material for fruits and vegetables. Carrageenan-based coatings have been applied to fresh fruits and vegetables such as fresh apples for reducing moisture loss, oxidation, or disintegration of the apples (Bryan 1972; Lee and others 2003). In combination with antibrowning agents such as ascorbic acid, carrageenan-based coatings resulted in positive sensory results and reduction of microbial levels on minimally processed apple slices (Lee and others 2003). By acting as a sacrificial moisture layer, carrageenan coating was able to protect moisture loss of grapefruits (Bryan 1972). In addition, κ-carrageenan films can effectively carry food-grade antimicrobials such as lysozyme, nisin, grape fruit seed extract, and EDTA for a wide range of applications as a food package material (Choi and others 2001).

Other gums, including exudate gums (gum arabic or acacia gum and gum karaya) and microbial fermentation gums (xanthan gum), have also been studied as coating materials for fruits and vegetables. Xanthan gum provides uniform coatings with good cling and improved adhesion in wet batters. Gum arabic has been used for coating pecan nut halves to eliminate moist and oily appearance (Arnold 1968). Spraygum and Sealgum (Colloides Naturels Inc., Bridgewater, N.J., U.S.A.), water-soluble adhesive film-forming polymers based on acacia gum, showed considerable promise as an inhibitor of after-cooking darkening of potatoes (Mazza and Qi 1991).

Other interesting polysaccharide-based coatings

Chitosan. Chitosan, a linear polymer of 2-amino-2-deoxy-β-D-glucan, is a deacetylated form of chitin, a naturally occurring cationic biopolymer (BeMiller 1965; Davis and others 1988; Tharanathan and Kittur 2003). It occurs as the shell component of crustaceans (crab and shrimp), as the skeletal substance of invertebrates, and as the cell wall constituent of fungi and insects (Anonymous 1991). Applications of chitosan include flocculating agent, clarifier, thickener, gas-selective membrane, coating material, promoter of plant disease resistance, wound-healing factor agent, and antimicrobial agent (Brine and others 1991; Goosen 1997).

Chitosan has been one of the most promising coating materials for fresh produce because of its excellent film-forming property, broad antimicrobial activity, and compatibility with other substances, such as vitamins, minerals, and antimicrobial agents (Li and others 1992; Shahidi and others 1999; Park and Zhao 2004; Durango and others 2006; Chien and others 2007; Ribeiro and others 2007). Chitosan-based coatings have shown effectiveness in delaying ripening and decreasing respiration rates of fruits and vegetables (Krochta and others 1997; Vargas and others 2006), and reducing weight loss, color wilting, and fungal infection in bell peppers, cucumbers, and tomatoes (El Ghaouth and others 1991, 1992a, 1992b). A commercial fruit coating, Nutri-Save (Nova Chem, Halifax, Canada), was developed to serve as both film former and natural preservative and to create a modified atmosphere for whole apples and pears to reduce respiration rate and desiccation of these commodities (Elson and others 1985). Another very attractive function of chitosan is its broad antifungal property (Allan and Hadwiger 1979; Stossel and Leuba 1984; Hirano and Nagao 1989), by inducing a plant-defense enzyme, chitinase, in plant tissues, which degrades fungal cell walls (Hirano and Nagao 1989). The fungistatic property of chitosan coating, which inhibits spore germination, germ tube elongation, and growth of pathogens (Botrytis cinerea and Rhizopus stolonifer), has been reported by several researchers. Zhang and Quantick (1998) demonstrated the antifungal effects of chitosan coating on fresh strawberries and raspberries during cold storage. Iverson and Ager (2003) invented a chitosan-based antifungal coating mixed with an edible wax emulsion and/or a preservative such as sodium benzoate, and/or an adhesion additive such as zinc acetate, and/or a wetting agent to have a molecular weight sufficient to form a composition having a solid content of about 15% or higher. Han and others (2004a, 2004b) reported chitosan coatings for extending shelf life of fresh strawberries and red raspberries by decreasing weight loss and delaying changes in color, titratable acidity, and pH during cold storage, and reducing the drip loss and improving the texture quality of frozen-thawed strawberries. Park and others (2005) demonstrated the antifungal function of chitosan coatings on fresh strawberries through a microbial challenge study and showed the excellent compatibility of chitosan with other antifungal agents. Vargas and others (2006) evaluated high molecular weight chitosan combined with oleic acid for preserving the quality of strawberries and found that the addition of oleic acid not only enhances chitosan antimicrobial activity but also improves water vapor resistance of coated samples. Chien and others (2007) further reported the effectiveness of chitosan coating for prolonging quality and extending shelf life of sliced mango fruit. In addition, chitosan-based coatings can carry high concentrations of vitamins and minerals for increasing the content of these nutrients in the fresh and frozen fruits without altering its antifungal and moisture-barrier functionality (Han and others 2004a, 2004b).

Aloe vera. *A. vera* is a tropical and subtropical plant that has been used for centuries for its medicinal and therapeutic properties (Eshun and He 2004). Recently, there has been increased interest in using *A. vera* gel as a functional ingredient in drinks, beverages, and ice cream (Moore and MacAnalley 1995), and as an edible coating material for fruits and vegetables (Martínez-Romero and others 2003) driven by its antifungal activity (Saks and Barkai-Golan 1995; Jasso de Rodríguez and others 2005). *A. vera* gel-based edible coatings have shown to prevent loss of moisture and firmness, control respiratory rate and maturation development, delay oxidative browning, and reduce microorganism proliferation of sweet cherries (Martínez-Romero and others 2005) and table grapes (Valverde and others 2005).

Protein-based coatings

Edible coatings made of animal proteins (such as milk protein) and plant proteins (such as zein, soy protein, and wheat gluten) exhibit excellent oxygen, carbon dioxide, and lipid-barrier properties, particularly at low RH (Gennadios and others 1994; Torres 1994; Baldwin and Baker 2002). Protein-based films and coatings are brittle and susceptible to cracking due to the strong cohesive energy density of the polymers (Lim and others 2002). The addition of compatible plasticizers can improve the extensibility and viscoelasticity of the films (Brault and others 1997; Sothornvit and Krochta 2001). Similar to polysaccharide films, protein films exhibit relatively poor water-barrier characteristics (Kester and Kennema 1986; McHugh and Krochta 1994a), attributed to the inherent hydrophilicity of proteins and the hydrophilic plasticizers incorporated into the film matrix to impart adequate flexibility (Sothornvit and Krochta 2000).

Plant origin. Zein and soy protein are the 2 major plant origin proteins studied as coating materials for fruit and vegetable applications. Zein is the key storage protein of corn and comprises approximately 45% to 50% of the proteins in corn (Shukla and Cheryan 2001). The ability of zein and its resins to form tough, glossy, and hydrophobic grease-proof coatings and their resistance to microbial attack have been of commercial interest (Pomes 1971). Zein-based coatings have water vapor permeabilities lower than or similar to those of other protein-based coatings (Krochta 1992), but much higher than that of LDPE (low-density polyethylene) (Bakker 1986). Its O_2 and CO_2 permeability is also lower than that of polysaccharides, polysaccharides/lipid composite coatings (Greener and Fennema 1989), as well as common plastic films such as LDPE, propylene, polystyrene, and polyvinyl chloride (Billing 1989), but higher than that of gluten coatings (Gennadios and others 1993).

Zein-based coatings have been applied to nuts and fresh and dried fruits, often as a substitute for shellac coatings. Zein coatings were able to retard ripening of tomatoes (Park and Chinnan 1990; Park and others 1994a, 1994b), to maintain the original firmness and color of broccoli florets (Rakotonirainy and others 2001), to provide a continuous adhesive and stable coating with satisfactory sensory properties, and to reduce the growth of *Listeria monocytogenes* on cooked sweet corn (Carlin and others 2001). Compared to commercial shellac coatings, zein coatings are favorable for gloss and other quality characteristics on apples (Bai and others 2002, 2003a, 2003b). However, the ethanol solvent system for making zein coatings leads to potential safety and environmental concerns (Sawyer 1997). The government regulation of volatile organic compound

(VOC) emissions has forced confectionery manufacturers to seek alternatives to VOC-containing coatings.

Soy protein concentrate (SPC) or soy protein isolate (SPI) is extracted from defatted protein meal and contains 65% to 72% and 90% protein on a dry basis, respectively (Mounts and others 1987). SP coatings are typically prepared from SPI with the addition of a plasticizer, commonly glycerol and sorbitol, for improving flexibility (Gennadios and others 1994). SP coatings generally exhibit poor moisture resistance and water vapor barrier properties due to the inherent hydrophilicity of the protein and the addition of hydrophilic plasticizers (Rhim and others 2000). In contrast, SP coatings are potent oxygen barriers, especially in low relative humidity environments (Gennadios and others 1993; Ghorpade and others 1995). The high oxygen-barrier capability of SPI coatings has led to their applications as microencapsulating agents of flavors and pharmaceuticals, or in coatings of fruits, vegetables, and cheese (Petersen and others 1999), where the SP coatings are able to preserve freshness of apple slices (Kinzel 1992) and to retard the senescence process of kiwifruit (Xu and others 2001).

Animal origin. Milk proteins such as whey protein and casein are important materials for edible films and coatings based on their numerous functional properties (Chen 1995, 2002; Krochta 1997, 2002). Caseins represent about 80% of the total milk proteins (Dalgleish 1989) and can form films from aqueous solutions without further treatment based on their random-coil nature and the ability to form extensive intermolecular hydrogen, electrostatic, and hydrophobic bonds, resulting in an increase of interchain cohesion (Ho 1992; Avena-Bustillos and Krochta 1993; Gennadios and others 1994; Brault and others 1997). The ability to function as a surfactant makes casein a very promising material for the formation of emulsion films. Casein films, being transparent, flavorless, and flexible, are attractive for food applications.

Pure caseinate/glycerin films are highly water soluble and permeable. Buffer treatments at the isoelectric point of the films helped reduce water solubility, but no improvement in water vapor resistance was observed (Krochta and others 1990). Casein coatings did not show any significant effect on reducing moisture loss of coated raisins during storage (Watters and Brekke 1961), while casein-based emulsion films (emulsified with lipid-based materials) were more effective than pure caseinate films in controlling moisture loss of fruits and vegetables (Krochta and others 1990).

Whey proteins, representing 20% of total milk proteins, are soluble in milk serum during cheese processing (Brunner 1977). Whey proteins are commercially purified to produce whey protein concentrate (WPC) with 25% to 80% protein content or whey protein isolate (WPI) with protein content above 90% (Krochta 1992, 2002). Whey proteins, when appropriately processed, produce transparent, flavorless, and flexible films, similar to caseinate films. Heat denaturation of the proteins produces insoluble whey protein films as a result of formation of intermolecular disulfide bonds (Gennadios and others 1994; McHugh and others 1994). Whey protein-based films possess excellent oxygen-barrier property in low and intermediate RH, comparable to the synthetic polymer films (Maté and Krochta 1997; Trezza and Krochta 2002); they also are good grease barriers (Chan and Krochta 2001; Lin and Krochta 2003). Due to the hydrophilic nature of whey proteins, the films are not good moisture barriers. Plasticizer addition into the denatured film solution improves film flexibility, but increases water vapor permeability of the films (McHugh and others 1994;, McHugh and Krochta 1994a, 1994b).

Caseinate-based and whey protein-based coatings have been applied on raisins, frozen peas, and peanuts to provide a barrier to oxygen and moisture transfer for extending shelf life of the products (Chen 1995; Maté and Krochta 1995). Caseinate and WPI coatings were reported to efficiently delay browning of apple and potato slices by acting as oxygen barriers (Le Tien and others 2001). Such coatings, together with modified atmosphere packaging, protected carrots against dehydration and helped retain their firmness during storage (Lafortune and others 2005). Milk proteins are important functional ingredients. Their solubility in aqueous solutions and unique surface characteristics (the balance of hydrophilic and hydrophobic forces) make them excellent emulsifiers. Hence, whey proteins are excellent candidates for developing composite or emulsion coatings with improved moisture-barrier property (Lee and others 2003; Certel and others 2004).

Emulsion and bilayer coatings

Recent emphasis and interest in the development of edible coatings have been focused on composite or bilayer coatings, such as integrating proteins, polysaccharides, and/or lipids together for improving functionality of the coatings. This is based on the fact that each individual coating material has some unique, but limited, functions and that together their functionality can be enhanced. Polysaccharides and proteins are polymeric and hydrophilic in nature, thus good film-formers with excellent oxygen, aroma, and lipid barriers at low relative humidity. However, they are poor moisture barriers compared to synthetic moisture-barrier films such as low-density polyethylene (LDPE). On the other hand, lipids are hydrophobic with better moisture-barrier properties than those of polysaccharides and proteins. However, the nonpolymeric nature limits their cohesive film-forming capacity (Krochta 1997). In composite films and coatings, the polysaccharide or protein provides the film integrity and entraps the lipid component, and the lipid component imparts the moisture-barrier property (Krochta 1997).

Composite film/coating can be categorized as a bilayer or a stable emulsion. For bilayer composite films/coatings, lipid generally forms an additional layer over the polysaccharide or protein layer, while the lipid in the emulsion composite films/coatings is dispersed and entrapped in the matrix of protein or polysaccharide. The amphiphilic character of proteins enables proteins to stabilize the protein–lipid emulsions through the balance between forces, primarily electrostatic and hydrophobic. Polysaccharides stabilize emulsions by strongly attaching to the surface of the lipid and significantly protruding into the continuous phase to form a polymeric layer or a network of appreciable thickness (Callegarin and others 1997). In many cases, addition of emulsifier is required to improve emulsion stability.

The barrier and mechanical properties of the composite films/coatings are affected by the composition and distribution of the hydrophobic substances in the film/coating matrix (Kamper and Fennema 1985; Debeaufort and others 1993). In general, bilayer films/coatings are more effective water vapor barrier than emulsion films/coatings due to the existence of a continuous hydrophobic phase in the matrix, and their moisture-barrier property can be improved by increasing the degree of lipid saturation and chain length of fatty acids (Kamper and Fennema 1984a, 1984b; Hagenmaier and Shaw 1990). For emulsion composite films/coatings, the type of lipid, location, volume fraction, polymorphic phase, and drying conditions significantly impact moisture-barriers property (Gontard and others 1994). Moisture barriers of whey protein–lipid emulsion films/coatings are improved when the hydrocarbon chain length of fatty acid alcohols and monoglycerides increased from 14 to 18 carbon atoms (McHugh and Krochta 1994a). Beeswax and fatty acids are more effective in reducing water vapor permeability of WPI-based emulsion films/coatings than fatty acid alcohols due to the lipid polarity.

The improved moisture-barrier properties of composite coatings have made them promising candidates for coating fresh and minimally processed fruits and vegetables. Cole (1969) reported that a bilayer coating formed with amylose ester of fatty acids and protein prevents dehydration and oxidative degradation of fruits and vegetables. Composite coatings with soy or zein protein with amylose ester or fatty acids provided an effective moisture barrier on carrot and fresh-cut apple slices (Williams 1968). Wheat gluten with lipid (beeswax, stearic acid, and palmitic acid) based bilayer coatings significantly retained firmness and reduced weight loss of fresh strawberries (Tanada-Palmu and Grosso 2005). Chitosan–lauric acid composite coatings prevented fresh-cut apple slices from browning and water loss (Pennisi 1992). A casein–lipid emulsion coating formed a tight matrix that binds to the cut apple surfaces and protects apple slices from moisture loss and oxidative browning (Krochta and others 1988, 1990). A sodium caseinate/stearic acid emulsion coating reduced white blush and respiration rate of peeled carrots, and a calcium caseinate acetylated monoglyceride emulsion coating reduced water loss of apples, celery sticks, and zucchini as a result of increased water vapor resistance of the emulsion coatings (Avena-Bustillos and others 1994a, 1994b, 1997). Caseinate–lipid emulsion coatings offer advantages over commercial wax coatings in that they can be applied to fresh produce at room temperature. The protein matrix also improves adhesion of the coatings to food surfaces. HPMC–lipid composite coatings consisting of beeswax or shellac significantly reduced texture loss and internal breakdown of plums (Perez-Gago and others 2003a). Composite coatings prepared from WPI or WPC as the hydrophilic phase and beeswax or carnauba wax as the lipid phase exerted an antibrowning effect on fresh-cut apples (Perez-Gago and others 2003b, 2005, 2006). Locust bean gum, shellac and beeswax coatings prolonged the storability of the cherries by reducing moisture loss (Rojas-Argudo and others 2005). An emulsion coating with CMC as the hydrophilic phase and paraffin wax, beeswax, or soybean oil as the hydrophobic phase also extended shelf life and reduced weight loss of apples, peaches, and pears (Toğrul and Arslan 2004, 2005).

Analytical Techniques for Measuring Edible Coatings Applied on Fruits and Vegetables

For evaluating the effectiveness of an edible coating applied on fruits and vegetables, quality parameters of coated products are usually measured as indicators. These parameters may include water loss, respiration rate, texture, color, microbial number, pH, total acidity, and soluble solid contents of the produce during storage. Meanwhile, direct measurements on the coating itself can be very valuable too although they may be more difficult to do. Some of the important coating functionalities include water and gas permeabilities of coatings, coating thickness, and surface wettability, morphology, and adherence of the coatings. Most of the food quality parameters can be measured by using standard procedures and have been well documented in the literature, and thus are not discussed here. This section provides a brief review of the analytical techniques for measuring those less commonly measured, but important parameters for understanding the coating effectiveness, such as internal gas composition of coated products, coating thickness, and surface characteristics of coatings.

Internal gas composition of coated produce

The internal gas modification in coated fruits and vegetables directly reflects the capability of a coating for modifying the internal gas atmosphere of produce. It is also indirectly related to the coating thickness through coating gas resistance parameters (Hagenmeier and Baker 1994, 1995), and through the solid concentration of the coating solutions (Park and others 1994a, 1994b). Hence, internal O_2 and CO_2 concentrations are important indicators of the effectiveness of a coating. Procedures for extracting and analyzing internal gas samples from plant tissues were described by Saltveit (1982) and Park (1999) in great detail. Based on Saltveit's procedures (Saltveit 1982; Cisneros-Zevallos and Krochta 2003), internal gas is sampled with a small volume syringe (5 mL) having a sidehole needle. To avoid external gas contamination, the fruits or vegetables are sampled under water. Once the gas is withdrawn, the needle is removed and a rubber stopper is used to seal the syringe under water. The syringes are then removed from the water and the gas samples contained in the sealed syringes are transferred to 1-mL syringes by introducing the needles through the rubber stopper. By using this positive pressure, contamination was avoided. Approximately 2-mL samples obtained from each fruit were then measured for the O_2 and CO_2 concentration by a gas chromatography or other gas analyzers (Diab and others 2001; Cisneros-Zevallos and Krochta 2003).

In the procedures described by Park (1999), a cylindrical plug of tissue is removed from individual fruits (orange, apple, tomato, cantaloupe, watermelon, and pineapple) using a rubber stopper corer. A glass tube is sealed around the hole in the surface of the produce sample. In order to measure internal gas composition, gas in the glass tube is allowed to equilibrate with internal gases. Then a gas sample is taken from the glass tube with a syringe injected through the sealing stopper. By immersing both the produce sample and the attached glass tube in water, atmospheric contamination at the point of syringe insertion can be prevented. Gas samples are then analyzed using the same procedures as described above. Required equilibrium times (when gas composition of the inside of the glass tube is constant) need to be determined by periodically monitoring gas changes inside the glass tube. Equilibrium time is expected to vary with variety, ripeness, temperature, and harvesting season for various fruits, but 2 h is usually enough time.

Coating thickness

The thickness of coatings is an important parameter as it directly affects the functionality of the coatings, typically the permeability of the coatings to water and gases. Coatings exceeding a critical thickness can cause detrimental effects of reduced internal O_2 concentration and increasing CO_2 concentration from anaerobic fermentation. Coating thickness depends on the solution properties such as density, viscosity, and surface tension, as well as surface withdrawal speed from the coating solution (Cisneros-Zevallos and Krochta 2003). The coating thickness can be determined destructively or undestructively. The former method is usually peeling the coating from the surface of the coated produce following the direct measurement of the film thickness using a micrometer. Although metric measurement is simple, it cannot be used for the coatings directly on the food surface, and peeling the coating from coated produce can be very difficult sometimes. Recently, confocal Raman microspectrometry (CRM), surface enhanced Raman scattering (SERS), and Fourier transform (FT)-Raman spectrometer have been utilized to analyze coating thickness directly from the surface of coated foods (Ghygesen and others 2003; McAnally and others 2003; Hsu and others 2005). In both CRM and SERS methods, samples are excited by a visible light source of which the Raman signal is readily overwhelmed by the strong fluorescence interference intrinsically arising from foodstuffs. While applying FT-Raman spectrometer, the laser line is introduced and shone directly onto the surface of the sample and the thickness of the coatings is analyzed by the FT-Raman spectrometer according to the simple linear regression on the calibration plot developed. According to Hsu and others (2005), FT-Raman spectroscopy has advantages in food-related study, such as (1) free from fluorescence interference, (2) less photodecomposition as compared to classical dispersive Raman measurement,

(3) allowing direct sample measurement with no sample destruction, and (4) no consuming of unfriendly reagents.

Different theoretical approaches have also been used to estimate film thickness from coating solution properties (Levich 1962; Groenveld 1970; Scriven 1988; Derjaguin 1993). Cisneros-Zevallos and Krochta (2003) applied the physical principles of the dip coating process to apples and defined the relationship between the coating thickness, the properties of the coating solution, and the internal gas modification of fruits. It was found that coating thickness varies with viscosity, concentration, density, and draining time of the biopolymer solution, and relates to the square root of viscosity and the inverse square root of draining time, which agrees with the theoretical approach for flat plate dip-coating in low-capillary-number Newtonian liquids.

Wettability

Edible coatings must wet and spread on the surface of the produce uniformly and upon drying form a coating that has adequate adhesion, cohesion, and durability to function properly (Krochta and Mulder-Johnston 1997). The effective spreading of a coating solution on the surface of fruits and vegetables is greatly influenced by the wettability of coating solutions, which in turn determines coating thickness and the effectiveness of coatings for fruits and vegetables. Choi and others (2002) discussed the theoretical background of the wettability measurement. Basically, the wettability of a solid by a liquid is determined by the balance between adhesive forces of the liquid on the solid and cohesive forces of the liquid, where adhesive forces cause the liquid to spread over the solid surface while cohesive forces cause it to shrink. The contact angle of a liquid drop on a solid surface is defined by the mechanical equilibrium of the drop under the action of 3 interfacial tensions: solid–vapor, solid–liquid, and liquid–vapor. This equilibrium relation is known as Young's equation (Rulon and Rorbert 1993). When a solid is contacted by a liquid in the presence of vapor, the liquid will adhere well on the solid surface if the total free energy required for the creation of the new interface decreases. The physical significance of this energy change is the work needed to separate the solid and liquid from the solid/liquid interface. Choi and others (2002) investigated wettability of chitosan coating solutions on 'Fuji' apple skin using the Du Nouy ring method and the sessile-drop method. Contact angle was measured by the sessile drop method and observed with a Face contact anglemeter. Surface tension of the coating solution was measured with a surface tensiometer equipped with a platinum ring. To calculate the surface tension components for coating solutions, interfacial tension measurements were performed with a platinum ring according to the Du Nouy ring method described by Harkins and Jordan (1930). Estimation of the critical surface tension of apple skin was attained by extrapolation from Zisman plots (Zisman 1964). Zisman plots have long been used to characterize the wettability of low-energy surfaces.

Surface characteristics of coatings

Surface characteristics of coatings, such as coating coverage and adhesion on the surface of coated fruits and vegetables and the surface glossiness, can be observed by various analytical instruments. For example, the surface morphologies of coated apple skin can be observed using a scanning electron microscope (Choi and others 2002; Fornes and others 2005). The uniformity of the coatings and adherence to the fresh-cut apples can be monitored using a Leica stereomicroscope coupled to a computer and a camera (Rojas-Graü and others 2007), where the cross sections of the coated fruits are obtained and samples were colored with a solution of toluidine blue. Surface gloss can be measured using a Micro-TRI-Gloss meter in accordance with American Society for Testing and Materials method D523.11 (Trezza and Krochta 2001) at 20°, 60°, and 85° angles from normal to the coating surface. In addition, confocal Raman microspectrometry (CRM), surface enhanced Raman scattering (SERS), and Fourier transform (FT)-Raman spectrometer can be utilized to analyze coating structure and surface characteristics too (Hsu and others 2005).

Incorporation of Functional Ingredients into Coating Matrix for Enhancing Coating Functionality

One of the unique functions of edible coatings is the capability to incorporate functional ingredients into the matrix to enhance its functionality. This may include:

1. improving basic coating functionality, such as plasticizers for improving mechanical properties and emulsifiers for stabilizing composite coatings and improving coating adhesion; and
2. improving quality, stability, and safety of coated foods by incorporating antioxidants, antimicrobial agents, nutraceuticals, flavors, and/or color agents.

A plasticizer, in most cases, is required for making edible coatings, especially for polysaccharide- and protein-based coatings since the structure of such coatings is often brittle and stiff due to extensive interactions between polymer molecules (Krochta 2002). Glycerol, acetylated monoglyceride, polyethylene glycol, and sucrose are common plasticizers incorporated into the polymeric coating matrix for decreasing glass transition temperature of the polymers and increasing coating flexibility (Guilbert and Gontard 1995). Plasticizers are usually hygroscopic that attracts water molecules. Water can also function as plasticizer, but easily lost due to dehydration at a low relative humidity environment (Guilbert and Gontard 1995). In addition to improving mechanical properties, the plasticizer also affects the resistance of coatings to the permeation of vapors and gases (Sothornvit and Krochta 2000, 2001), where the hydrophilic plasticizers usually increase the water vapor permeability of the coatings.

Emulsifiers are surface-active agents of an amphiphilic nature and are able to reduce the surface tension of water–lipid or water–air interface. Emulsifiers are essential for the formation of protein or polysaccharide coatings containing lipid emulsion particles. Emulsifiers also modify surface energy to control adhesion and wettability of the coating surfaces (Krochta 2002). Addition of an emulsifier into whey protein coatings increases the hydrophilicity and coatability of peanut surfaces, thus improving oxygen barrier of the coatings (Lin and Krochta 2005).

Other functional ingredients, such as antioxidants, antimicrobials, nutraceuticals, flavor, and color agents, can be carried by edible coatings and retained on the food surface for enhancing food quality, stability, and safety. Common antimicrobial agents used in food systems, such as benzoic acid, sodium benzoate, sorbic acid, potassium sorbate, and propionic acid, may be incorporated into coatings. Starch-based coatings containing potassium sorbate were applied on the surface of fresh strawberries for reducing microbial growth and extending storage life of the fruit (Garcia and others 1998). HPMC coating containing ethanol was effective in inactivating *Salmonella montevideo* on the surface of fresh tomatoes (Zhuang and others 1996). Lysozyme was incorporated into chitosan coatings for enhancing the antimicrobial activity of chitosan against *Escherichia coli* and *Streptococcus faecalis* (Park and others 2004). In addition, chitosan coatings containing potassium sorbate were shown to increase antifungal activity against the growth of *Cladosporium* and *Rhizopus* on fresh strawberries (Park and others 2005). A new patented edible film comprising organic acids, protein, and glycerol (for example, 0.9% glycerol, 10% soy protein; and 2.6% malic acid) can inhibit pathogen growth, including *L. monocytogens*, *S. gaminara,* and *E. coli* 0157:H7. Such film also provides a method for coating comestible products with edible films without masking the color but increasing the shelf life (Hettiarachchy and Satchithanandam 2007).

Antioxidants can be added into the coating matrix to protect against oxidative rancidity, degradation, and discoloration of certain foods. Nuts were coated with pectinate, pectate, and zein coatings containing BHA, BHT, and citric acid to prevent rancidity and maintain their texture (Swenson and others 1953). Ascorbic acid was incorporated into edible coatings for reducing enzymatic browning in whole and sliced mushrooms (Nisperos-Carriedo and others 1992). Xanthan gum coatings mixed with α-tocopherol enhanced nutritional quality and improved the surface color of peeled baby carrots (Mei and others 2002). Carrageenan and whey protein coatings containing antibrowning agents such as ascorbic acid and citric acid effectively prolonged the shelf life of apple slices (Lee and others 2003). MC-based coatings containing ascorbic acid and sorbic acid were able to retard browning and to enhance texture of cut-pear wedges (Guadalupe and others 2003). Chitosan-based coating containing α-tocopheryl acetate significantly delayed the color change of fresh and frozen strawberries (Han and others 2004b).

Edible coating is an excellent vehicle to enhance the nutritional value of fruits and vegetables by carrying basic nutrients and/or nutraceuticals that are lacking or are present in only low quantity in fruits and vegetables. Xanthan gum coating was utilized to contain a high concentration of calcium and vitamin E for not only preventing moisture loss and surface whitening, but also significantly increasing the calcium and vitamin E contents of the carrots (Mei and others 2002). The development of chitosan coatings containing high concentrations of calcium, zinc, or vitamin E also provided alternative ways to fortify fresh fruits and vegetables that otherwise could not be accomplished with common processing approaches (Park and Zhao 2004). This application has been successfully demonstrated on fresh and frozen strawberries (Han and others 2004b). Flavor and coloring agents may also be added to edible coatings to improve the sensory quality of coated products. However, very little has been reported regarding this application.

Future Needs in Edible Coatings for Fruits and Vegetables

Despite significant benefits from using edible coatings for extending shelf life and enhancing quality and microbial safety of fresh and minimally processed fruits and vegetables, commercial applications on a broad range of fruits and vegetables are still very limited. This may be constrained by several factors, including limited understanding and availability of appropriate coating materials, poor moisture-barrier property, weak surface adhesion of some coating materials, potential allergenicity of protein-based coating materials, undesirable sensory quality of some coating materials, and feasibility of scale-up to an industrial setting. Research to overcome these constrains are discussed in the following sections.

Improvement of moisture-barrier properties of hydrophilic coatings

Hydrophilicity of some edible coating materials does not provide a sufficient moisture barrier for coating fruits and vegetables, especially for fresh-cut products, where a wet surface is present. Efforts are required to develop new coating materials and/or coating formulations that possess high moisture-barrier property and surface adhesion, and to understand the functionality and interactions among different components in the edible coating formula. Studies to improve the functionality of existing coating materials are also important. The incorporation of hydrophobic ingredients, such as lipids and fatty acids, for improving moisture barrier while still maintaining desirable functions of resistance to vapor, gas, or solute and sensory properties is critical in future research.

Improvement of coating adhesion and durability

Coating adhesion and durability are important for maintaining food quality during storage. In order to truly receive the benefit of edible coatings on fruits and vegetables in commercial applications, the coating must adhere to the food surface during processing, storage, and transportation. Surface wettability is essential for a good coating adhesion. A liquid would perfectly wet the solid when the surface tension of a solid is greater or equal to that of the liquid, which can be achieved by the addition of appropriate surfactant in the coating solutions. Adhesion of the coatings on the food surfaces with different characteristics needs to be studied and improved. This is typically important for some fresh and fresh-cut fruits and vegetables where a natural hydrophobic waxy layer or a high-moisture and wet surface is already present, respectively. In today's coating application, dipping is a common method for applying coatings. This method when using water containing detergent, however, may wash out the natural waxy layer on the surface of some fruits and vegetables, thus degrading the functionality of the coatings. Moreover, it may dilute the coating solution and result in significant residual (waste) of the coating materials. Hence, development of other coating application techniques such as spraying or dripping is necessary to increase coating efficiency and durability.

Continuous development of composite or microemulsion coatings

Composite coatings are promising in improving moisture-barrier properties of hydrophilic coating materials and improving coating adhesion and durability. Research on identifying the most compatible material combinations, the lipid particle size, and stability of the emulsion system needs to be continuously investigated for meeting the specific needs of coating fresh and minimally processed fruits and vegetables.

Sensory quality of edible coatings

Sensory quality is essential in determining the success of edible coatings as it affects consumer acceptance and market potential of coated products. Exogenous flavor impact by the coating materials, unattractive surface appearance of coatings, and other factors may affect consumer acceptance of the coated products. Therefore, it is important to investigate sensory quality of coating materials and coated products, including appearance, color, aroma, taste, and texture. Unfortunately, such studies are very scarce, and more works need to be done.

Scale-up of the coating operation in an industrial setting

Fruits and vegetables are fragile products with high water content, thus typically raising 2 challenges for scale-up coating applications in an industrial setting: (1) protecting fruits and vegetables from physical damage during the coating application while providing necessary coating adhesion and durability, and (2) preventing moisture loss and surface dehydration during drying after the coating application. Pan coating and fluidized-bed coating systems require intense tumbling, while dipping application may wash out the natural protective layer on the surface of some fruits and vegetables. Seeking more feasible coating application systems that provide uniform distribution of coating solution on the surface of fruits and vegetables and efficient drying is necessary in scale-up coating operations in a factory scale.

Conclusions

Edible coatings can protect perishable fresh produce from deterioration by retarding dehydration, suppressing respiration, improving texture quality, helping retain volatile flavor compounds and reducing microbial contamination. Along with increased market demand for fresh and minimally processed fruits and vegetables, edible coatings with unique functionality will certainly become more important in the future. Many of the polysaccharide-based and protein-based coatings, especially those of inherent antimicrobial or antifungal activities, are getting more interest as substitutes for traditional lipid coatings. These coatings generally are good oxygen barriers at low-to-intermediate relative humidity, but relatively poor moisture barriers. In order to satisfy the primary goal of reducing moisture loss of fruits and vegetables with edible coatings, continued efforts are necessary to develop stable emulsion coatings with desired moisture-barrier properties. Meanwhile, studies for improving coating adhesion and durability on the surface of fruits and vegetables and investigations on sensory quality and consumer acceptance of coated products are needed.

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