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# Coatings and Other Supplemental Treatments to Maintain Vegetable Quality

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## I. INTRODUCTION

Much of the world's harvested fresh produce never reaches the consumer's kitchen. Some losses are due to spoilage, while others are due to surface defects that render the product unmarketable. This is especially true when horticultural produce is shipped long distances from sites of harvest. Treatments have been developed to prolong the postharvest life of vegetables while maintaining acceptable market quality. Temperature control and use modified atmospheres (MA) and controlled atmospheres (CA) are among the most important techniques for maintaining vegetable quality after harvest. Other treatments, which are the subject of this chapter, include use of waxes or other edible coatings; use of compounds to control spoilage organisms; and chemical treatments to retard ripening, senescence, sprouting, and undesirable color and texture changes. Some horticultural produce can harbor larvae of various types of fruit flies and thus must go through quarantine procedures prior to export.

## II. EDIBLE COATINGS

Use of coatings on fruits and vegetables has been practiced for decades. Synthetic and natural waxes and resins have been used to coat fresh fruits and vegetables since the 1930s (Platenius, 1939), mainly for control of water loss and to improve appearance. However, recent consumer interest in nutrition, food safety, and environmental concerns has revitalized efforts in edible coating research. Alternatives to petroleum-based packaging include

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naturally occurring film formers and their derivatives. Recently, coatings have been used to slow down ripening and respiration of fresh produce in a manner similar to modified-atmosphere packaging (MAP).

## A. Materials

Edible coating film formers can include lipid, resin, protein, and carbohydrate compounds, used alone or in composite formulations. Some of the natural lipids are beeswax, carnauba wax, and candelilla wax. The petroleum-based waxes and oils used in coatings for vegetables are paraffin wax, polyethylene wax, and mineral oil (Hernandez, 1994). The petroleum-based lipid materials are generally restricted to use in edible coatings for fruits and nuts where the peel or shell is not normally ingested, including avocado, banana, citrus, coconut, mango, melon, papaya, pineapple, pumpkin, and different types of nuts in the shell (Eastman Chemicals, 1986; FDA. 21 CFR, 1996; Hernandez, 1994). Sucrose esters of fatty acids have also been used in conjunction with polysaccharides in edible coatings (Banks, 1984; Ukai et al., 1975) that may help prevent decay in fresh produce.

Resins are a group of acidic substances, many of which are wound-response products secreted by specialized plant cells of trees and shrubs. Synthetic resins are petroleum-based products (Hernandez, 1994). These compounds have relatively low permeability to gases while offering a moderate barrier to water vapor (Hagenmaier and Baker, 1995; Hagenmaier and Shaw, 1991, 1992). Shellac resin, secreted by the insect *Laccifer lacca* found in India; wood rosin, manufactured from oleoresins of pine trees; and coumarone indene resin, a petroleum-based product, have all been used in coatings for fresh produce. The latter two resins/rosins are restricted to use on citrus, however.

Proteins such as casein from milk and zein from corn have been used as edible coatings for vegetables such as peeled carrots (Avena-Bustillos et al., 1993) and tomatoes (Park et al., 1994). Film-forming proteins derived from plants include corn zein, wheat gluten, soy protein, peanut protein, and cottonseed protein, of which all but the latter are considered GRAS (‘‘generally recognized as safe,’’ FDA 21 CFR). Keratin, collagen, gelatin, casein, and milk whey proteins are film formers derived from animal sources, of which casein and whey proteins are GRAS. Proteins are moderately permeable to gases but offer little resistance to water vapor (Gennadios et al., 1994; Gennadios and Weller, 1990; McHugh and Krochta, 1994).

Polysaccharides comprise an abundant resource of hydrophilic film-forming agents with a wide range of viscosities, relatively low permeability to gases, but little resistance to water vapor transfer. These materials include cellulose and its derivatives, pectins, starches, chitosan (derived from chitin), and various gums (Nisperos-Carriedo, 1994). Several commercial coatings were developed from carbohydrate polymers, including TAL Pro-long (Courtaulds Group, London), Semperfresh (United Agriproducts, Greeley, CO), and Nature Seal (EcoScience Corp., Orlando, FL), which have cellulose as the major film former; and Nutri-Save (Nova Chem, Halifax, NS, Canada), made from chitosan, for use on fresh produce. Chitosan has not yet received approval for food use in the United States but is approved in Canada. Chitosan has antimicrobial properties and has been shown to inhibit growth of fungi on plants by inducing plant defense responses (Stossel and Leuba, 1984; Walker-Simmons et al., 1984).

Materials other than film formers are added to edible coatings to improve the structural, mechanical, or handling properties of a coating and to improve the quality (flavor, color, or nutritional properties) of the coated product. In the latter case, the coating acts

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as a carrier of useful compounds that have a desired effect on the coated item. Materials that improve coating performance include plasticizers, which are usually low-molecular-weight compounds that impart increased strength and flexibility to coatings. Addition of plasticizers, however, also increases coating permeability to water vapor and gases (Donhowe and Fennema, 1994; Kester and Fennema, 1986). Common plasticizers include polyols such as glycerol, sorbitol, mannitol, propylene glycol, and polyethylene glycol (molecular weight 200 to 9500). Sucrose, sucrose fatty-acid esters, and acetylated monoglycerides can also by used as plasticizers. Of these, glycerol, sorbitol, and propylene glycol are considered GRAS. Emulsifiers can be classified as macromolecular stabilizers or as surface-active agents. Macromolecular stabilizers are proteins, gums, and starch, which stabilize emulsions (Artz, 1990). Surface-active agents reduce surface water activity and can affect the rate of moisture loss from a food when used as a coating (Kester and Fennema, 1986).

## B. Effect on Water Loss

Vegetables lose water to the surrounding air in the form of water vapor in a process called transpiration. This entails the movement of water from cells to the surrounding atmosphere following a gradient of high water concentration [~100% relative humidity (RH) in intercellular spaces or internal atmosphere] to low water concentration (% RH of the storage environment). For this reason, fresh produce is often stored under conditions of high RH (90% to 98%) to minimize water loss, subsequent weight loss, and shriveling (Woods, 1990). Vegetables have a natural waxy coating, called a cuticle, made up of fatty acid–related substances (waxes and resins) with low water permeability. This waxy layer may be removed or altered during washing (Hagenmaier and Baker, 1993a), resulting in increased water loss and subsequent weight loss in uncoated commodities. Edible coatings can help retard this movement of water vapor (Hagenmaier and Baker, 1995), but they become more permeable to water vapor and gases under conditions of high RH because water acts like a plasticizer. Wax and oil coatings have been shown to retard desiccation of many vegetables. If pores, cracks, or pinholes occur in the film surface, mass transfer of water vapor through these areas may be much more rapid than dissolving and diffusion of water vapor through a film barrier (McHugh and Krochta, 1994). Water vapor transfer through films is dependent on the environmental conditions, such as temperature and humidity, as mentioned above, and thus should be tested under conditions that are expected to be encountered by a specific product. Generally, the more hydrophilic the film-forming material, the more permeable the film will be to water vapor. In most cases, lipid materials (wax and oil coatings) offer the most effective barriers to water vapor, followed by shellac, with the carbohydrate and protein coatings being least effective due to their hydrophilic characteristics. Reported uses of edible coatings to retard water loss of whole vegetables are given in Table 1.

## C. Effect on Internal Atmosphere

### 1. Effect on Ripening and Senescence

Cells of plant tissues, such as harvested vegetables, are physiologically active, using $O_2$ and releasing $CO_2$ as they respire (Kader, 1986; Wills et al., 1998) and thus creating a MA within a film or coating semipermeable barrier if present. Slight modification of the fruit's internal atmosphere can be beneficial for commodities that ripen after harvest (gen-

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**Table 1** Whole Vegetable Products to Which Edible Coatings Have Been Applied

| Product | Coating | Benefit | Reference |
|---|---|---|---|
| Asparagus | Carnauba, paraffin, shellac, gum, resin, mineral oil, emulsifiers | Retard water loss and shrinkage | Platenius, 1939 |
| Beet | Carnauba, paraffin, shellac, gum, resin, mineral oil, emulsifiers | Retard water loss and shrinkage | Platenius, 1939 |
| Broccoli | Polysaccharide film SOAFIL (carrageenan) | Delay senescence | Anonymous, 1992 |
| Carrot | Vegetable waxes (sisal, sugarcane and carnauba), mineral petroleum ± shellac | Retard water loss and lower respiration rates | Dalal et al., 1971 |
| | Carnauba, paraffin, shellac, gum, resin, mineral oil, emulsifiers; | Retard water loss and shrinkage | Platenius, 1939 |
| | Vegetable waxes, paraffin | Prolong shelf life | Dalal et al., 1971 |
| Cucumber | Carnauba, paraffin, shellac, gum, resin, mineral oil, emulsifiers | Retard water loss and shrinkage | Platenius, 1939 |
| | Carnauba, paraffin | Retard water loss and shrinkage | Mack and Janer, 1942 |
| | Vegetable waxes (sisal, sugarcane and carnauba), mineral petroleum ± shellac | Retard water loss and lower respiration rates | Dalal et al., 1971 |
| | Vegetable waxes, paraffin | Prolong shelf life | Dalal et al., 1971 |
| | Paraffin wax or mineral oil | Retard water loss | Lawrence and Iyengar, 1983 |
| | Commercial water wax | Retard water loss | Risse et al., 1987 |
| | Carnauba, polyethylene | Retard water loss and chilling injury | Purvis, 1994 |
| Eggplant | Paraffin wax or mineral oil | Retard water loss and shrinkage | Lawrence and Iyengar, 1983 |
| Kohlrabi | Carnauba, paraffin, shellac, gum, resin, mineral oil, emulsifiers | Retard water loss and shrinkage | Platenius, 1939 |
| Lima bean | Carnauba, paraffin, shellac, gum, resin, mineral oil, emulsifiers | Retard water loss and shrinkage | Platenius, 1939 |
| Melon | Paraffin wax | Reduce water loss | Barger et al., 1948 |
| | Vegetable wax, paraffin | Prolong shelf life | Delal et al., 1971<br>Bhatnagar et al., 1981 |
| | Carnauba, paraffin wax | Delay decay | Aharoni et al., 1992 |
| | Britex wax with fungicide (imazalil) | Delay decay | Aharoni et al., 1992 |
| Parsnip | Carnauba, paraffin, shellac, gum, resin, mineral oil, emulsifiers | Retard water loss | Platenius, 1939 |

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|---|---|---|---|
| Pepper | Carnauba wax | Retard water loss and improve nutrition | Habeebunnisa et al., 1963 |
| | Mineral oil | Retard water loss | Lerdthanangkul and Krochta, 1996 |
| | Cellulose | Retard water loss | Lerdthanangkul and Krochta, 1996 |
| | Milk protein | Retard water loss | Lerdthanangkul and Krochta, 1996 |
| Potato | Vegetable waxes (sisal, sugarcane, and carnauba), mineral petroleum, ± shellac | Retard water loss and lower respiration | Dalal et al., 1971 |
| | Lecithin, hydroxylated lecithin | Inhibition of chlorophyll and solanine synthesis | Wu and Salunkhe, 1972; 1978 |
| | Hot paraffin wax and corn oil | Inhibition of chlorophyll and solanine synthesis | Poapst et al., 1978 |
| | Tween surfactants | Inhibition of chlorophyll and solanine synthesis | Poapst et al., 1978 |
| Pumpkin | Carnauba, paraffin | Reduction of water loss | Platenius, 1939 |
| Rutabaga | Mineral oil, paraffin, beeswax, rosin | Retard water loss and shrinkage | Platenius, 1939; Hartman and Isenberg, 1956 |
| Snap bean | Carnauba, paraffin | Retard water loss and shrinkage | Platenius, 1939 |
| Squash | Carnauba, paraffin, shellac gum, resin, mineral oil, emulsifiers | Retard water loss and shrinkage | Platenius, 1939 |
| | Paraffin wax or mineral oil | Retard water loss and shrinkage | Lawrence and Iyengar, 1983 |
| Sweet potato | Paraffin wax or mineral oil | Retard water loss | Lawrence and Iyengar, 1983 |
| Tomato | Beeswax, paraffin, mineral oil | Reduce decay | Brooks, 1938; Ayres et al., 1964 |
| | Carnauba, paraffin, mineral oil | Retard water loss | Claypool and King, 1941 |
| | Vegetable waxes (sisal, sugar cane, and carnauba), mineral petroleum ± shellac | Retard moisture loss and lower respiration | Delal et al., 1971 |
| | Vegetable wax, paraffin | Prolong shelf life | Delal et al., 1971 |
| | Vegetable wax | Retard water loss | Lawrence and Iyengar, 1983 |
| | Fungicidal wax (SOPP) | Prolong shelf life, reduce decay | Hall, 1989 |
| | Cellulose | Delay ripening | Nisperos-Carriedo and Baldwin, 1988; Nisperos-Carriedo et al., 1991; Park et al., 1994 |
| | Chitosan | Prolong shelf life reduce decay | El Ghaouth et al., 1992 |
| Turnip | Paraffin wax | Retard water loss and improve appearance | Franklin, 1961 |
| | Paraffin wax or mineral oil | Retard water loss | Lawrence and Iyengar, 1983 |
| | Carnauba wax | Retard water loss and maintain color | Perkins-Veazie, 1991 |
| Vegetables, general | Carnauba, candelilla, paraffin waxes, emulsifiers, mineral oil | Retard water loss and shrinkage | Hartman and Isenberg, 1956 |
| | Liquid hydrocarbon wax plus solvent | Lubrication | Hartman and Isenberg, 1956 |

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erally climacteric fruits and vegetables). Ethylene production, like respiration, is a process that requires $O_2$. Generally, low $O_2$ (below 8%) and high $CO_2$ (above 5%) concentrations slow down respiration and retard ethylene production and therefore ripening (Kader, 1986), thus extending shelf life (see Chap. 9). High storage temperatures increase fruit or vegetable respiration (Wills et al., 1998) and exacerbate the effect of a coating on the internal atmosphere of coated produce. This situation increases the risk of coated commodities going anaerobic. Low temperature, on the other hand, slows down ethylene production and respiration, thus minimizing the effect of a film or coating on the internal atmosphere of coated produce and its indirect effect on ripening.

Highly gas-permeable materials such as polyethylene and carnauba wax control water loss, but do not promote much modification of the internal atmosphere. This is desirable for control of water loss without the risk of anaerobic conditions in the case of nonclimacteric vegetables. Resins, which have relatively low permeability to gases, can help control ripening but are more likely to create anaerobic conditions compared to other coating materials, especially in cases of temperature abuse (Hagenmaier and Baker, 1994a,b, 1996; Hagenmaier and Shaw, 1991). Carbohydrate and protein coatings are generally hydrophilic and thus do not effectively prevent water loss, but they can result in more modification of the vegetable internal atmosphere for control of ripening compared to resin materials (Baldwin, 1994; Baldwin et al., 1995). Reported uses of coatings to control ripening of vegetables are given in Table 1.

### 2. Effect on Flavor and Nutrition

Coating of fresh produce can result in flavor changes due to coating entrapment of volatiles or coating effects on metabolism. The latter may affect volatile synthesis (Baldwin et al., 1995; Nisperos-Carriedo et al., 1990), including ethanol (Baldwin et al., 1995; Davis and Hofman, 1973; Nisperos-Carriedo et al., 1990), which has been associated with ‘‘off’’ flavor in citrus (Cohen et al., 1990; Hagenmaier and Baker, 1993a, b). Positive effects of coating on flavor have been reported for carrots (Howard and Dewi, 1995). Use of a coating resulted in higher levels of carotenoids (vitamin A precursors) in peeled carrots (Chen et al., 1996) and ascorbic acid in pepper (Habeebunnisa et al., 1963).

## D. Effect on Appearance

Resins, zein protein, and microemulsions of waxes can impart high gloss to coated products (Hagenmaier and Baker, 1994a,b, 1995). For example, shellac is used on red apples and some citrus for the high-gloss finish that most consumers prefer. Polyethylene and carnauba wax microemulsions are also used on fruits and vegetables to control water loss and add shine (Baldwin, 1994). Zein has been tested on tomato fruit (Park et al., 1994) but thus far has not been used commercially on horticultural produce. Candelilla wax microemulsions tested on citrus fruit contributed a glossy appearance, especially when combined with gelatin protein (Hagenmaier and Baker, 1996). Candelilla coatings may prove useful for vegetable commodities. Carbohydrate coatings, such as pectin- or cellulose-based formulations, result in an attractive nonsticky sheen when applied to products and have been tested on tomato (Nisperos-Carriedo and Baldwin, 1988; Nisperos-Carriedo et al., 1991) and cucumber (Baldwin et al., 1997). However, they often make for an undesirable slippery texture when products become wet with condensation, as is often the case after removal from cold storage.

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A MA can also reduce other $O_2$-dependent reactions. Treating potatoes with paraffin wax and oil coatings reduced sprouting and synthesis of chlorophyll (green pigment) and solanine (toxic glycoalkaloid) without adversely affecting respiration (Salunkhe and Wu, 1979; Wu and Salunkhe, 1972). Polyoxyethylene sorbitan fatty acid esters (Tweens), lecithin, and hydroxylated lecithin surfactants applied as thin films also inhibited chlorophyll and solanine synthesis in the peel of potato tubers (Poapst et al., 1978; Wu and Salunkhe, 1978). The effect of these coatings on potato greening was thought to be due to creation of a MA (low $O_2$) within the tubers that affected synthesis of these undesirable compounds.

Conversely, coatings can also be used to prevent degreening of limes and even lemons (for the Japanese market, where consumers associate green color with freshness), attributed to a delay in chlorophyll breakdown. As with chlorophyll synthesis, inhibition of chlorophyll breakdown may be due to creation of a MA, since chlorophyll breakdown also requires $O_2$. This was demonstrated with a carbohydrate coating (Baldwin et al., 1997; Chen and Grant, 1995) and for limes coated with mineral oil (Baldwin et al., 1997). Such treatments could be useful for cucumber to delay yellowing.

Peeled carrot pieces undergo discoloration due to dehydration of the surface, and this white blush is a major factor reducing consumer acceptance of this product (Avena-Bustillos et al., 1993; Howard and Dewi, 1995; Sargent et al., 1994). Coatings have been used to reduce water vapor permeability on the surface of the peeled carrot tissue and subsequent discoloration. A cellulose/protein-based coating carrying antibrowning agents delayed browning of cut potato (Baldwin et al., 1996; Mazza and Qi, 1991) and a sucrose ester coating suppressed browning of shredded cabbage (Sakane et al., 1990). Reported uses of coatings that affect appearance or flavor of fresh-cut vegetables are summarized in Table 2.

## E. Effect on Decay

Coatings on fruits and vegetables can also act as lubricants to reduce surface injury, scarring, and chafing (Hardenburg, 1967; Hartman and Isenberg, 1956). With less wounding of the fruit, decay due to opportunistic wound pathogens is lessened. In addition, applying

**Table 2** Fresh-Cut Vegetable Products to Which Edible Coatings Have Been Applied

| Product | Coating | Benefit | Reference |
|---|---|---|---|
| Shredded cabbage | Sucrose fatty acid esters | Reduce discoloration (browning) | Sakane et al., 1990 |
| Peeled carrot | Sodium caseinate, stearic acid | Reduce discoloration (white blush) | Avena-Bustillos et al., 1993 |
| | Cellulose | Reduce discoloration (white blush) | Sargent et al., 1994; Howard and Dewi, 1995 |
| | | Improve nutrition | Chen et al., 1996 |
| Peeled potato | Gum acacia w/w/o gelatin (Spraygum and Sealgum) + $CaCl_2$ | Reduce discoloration (browning) | Mazza and Qi, 1991 |
| | Cellulose, soy protein + antioxidants | Reduce discoloration (browning) | Baldwin et al., 1996 |

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certain types of coatings with biocontrol agents (McGuire and Baldwin, 1994; Potjewijd et al., 1995) or acidulants and preservatives (Baldwin et al., 1996) reduces surface microbial populations on some commodities. Waxing of citrus, for example, resulted in less decay compared to unwaxed fruit (Waks et al., 1985). This has also been reported for carnauba-waxed cucumber (Baldwin et al., 1997; Mack and Janer, 1942). Cut potato treated with a coating carrying an acidulant and preservative showed reduced microbial populations compared to controls (Baldwin et al., 1996). However, waxed cucumber stored at low temperature (7°C) exhibited increased decay compared to unwaxed fruit (Risse et al., 1987). Paraffin-coated cucumbers also showed increased decay attributed to anaerobic conditions resulting from the thickness of the coating application (Bhatnagar et al., 1981). In some cases, coated tomatoes also had a higher incidence of decay (Ayres et al., 1964).

Fresh fruits and vegetables are susceptible to a variety of postharvest decays that can be reduced by treatment with fungicides with and without a coating or ‘‘wax.’’ Fungicides are applied as drenches prior to waxing or in solvent or water waxes. This results in reduced ability to inhibit mold growth, however, compared to application as an aqueous suspension as has been shown in melon and citrus (Aharoni et al., 1992; Brown, 1984). It is thought that encapsulation of the fungicide in the wax is the reason for its reduced efficacy (Brown, 1984). Use of fungicides in fruit coatings has been reported for strawberries treated with 3-(3,5-dichlorophenyl *0-N*-(1-methylethyl)-2,4-dioxo-1-imidazolidine-carboxamide (iprodione or Rovral®) (El Ghaouth et al., 1991), and tomatoes treated with *N*-[(trichloromethyl)thio]-4-cyclohexene-1,2-dicarboximide (captan) and o-phenylphenol (Domenico et al., 1972; Hall, 1989).

Antagonistic yeasts and bacteria have been shown to inhibit growth of molds and thus prolong shelf life of fresh and fresh-cut fruits and vegetables (Breidt and Fleming, 1997; Droby et al., 1991; Wisniewski and Wilson, 1992). The mechanisms of action are reported to be the production of an antibiotic compound, competition for nutrients at wound, direct interaction with the pathogen, and induction of host defense responses (Wisniewski and Wilson, 1992). These compounds are generally applied prior to coating or waxing; but when applied in fruit coatings, they were shown to delay spoilage of citrus fruit (McGuire and Baldwin, 1994; Potjewijd et al., 1995). This technology may be useful for vegetable commodities if biocontrol agents are developed for such crops. Already, several yeasts and an antagonistic bacterium have been reported to control decay organisms on strawberry and tomato, respectively (Lima et al., 1997; Mari et al., 1996) Two commercial products that are approved and available on the U.S. market are BioSave® (EcoScience Corp.), which contains an antagonist bacterium, and Aspire® (Ecogen Corp., Langhome, Pa.), which contains an antagonist yeast for control of decay on apples and citrus fruits.

## III. ANTIMICROBIAL TREATMENTS

Use of fungicides, methods of washing fruit, and use of antimicrobial drenches (e.g., sodium *o*-phenylphenate, or SOPP) are covered more extensively in other chapters of this book. Chlorinated water has been used commercially to reduce decay for over 20 years. Hypochlorous acid is a strong oxidizing agent that inactivates microbes and reacts with organic and inorganic matter. Chlorine’s effectiveness is thus reduced if organic matter is in the dump tanks or flumes (Bartz, 1988). Vegetables have been treated with chlorine in various ways, but a concentration of 100 to 150 μg $L^{-1}$ free chlorine for whole fruits and vegetables is recommended. Use of chlorine as hypochlorous acid/hypochlorite ion

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or chlorine dioxide in dump tanks reduced postharvest disease in tomato (Bartz, 1988). Sodium hypochlorite and chlorinated water have been used to reduce decay of cassava (Plumbley and Rickard, 1991) and asparagus (Kesta and Piyasaengthong, 1994). Chlorinating hydrocooler water reduced decay in strawberry (Ferreira et al., 1996). Mushrooms sprayed with calcium hypochlorite solutions exhibited reduced microbial counts (Kuyper et al., 1993). Use of surfactants with chlorine in packinghouse water may improve decay control, as was found with pear (Spotts and Peters, 1982). Fresh-cuts such as spinach are also washed in 50 to 200 μg $L^{-1}$ chlorine to reduce microbial loads (Watada et al., 1996). The pH of the chlorinated water should be maintained at 7 for maximum biocidal activity (Brown and Wardowski, 1984). Hypochlorite also was shown to inhibit enzymatic browning of cut potato and green beans at 17.5 to 140 μg $L^{-1}$ and pH 4 to 11, comparable to treatment with antioxidants such as ascorbic acid and bisulfite (Brecht et al., 1993).

## A. Preservatives and Acidulants

### 1. Preservatives

Preservatives and acidulants (pH control or flavoring agents) can be applied directly or in coatings for whole and fresh-cut vegetable products (Cuppett, 1994). Preservatives include short-chain organic acids (benzoates and sorbates), alkyl esters of *p*-hydroxybenzoic acid (parabens), and sulfites. Sulfites, however, are no longer allowed for use on raw fruits and vegetables due to the elicitation of allergenic responses in a certain segment of the population (Davidson and Juneja, 1990; Pollard, 1991). Use of coatings as carriers of preservatives such as benzoates and sorbates improved their performance when applied to cut fruit or cheese analogues. This may be due to prevention of diffusion of preservatives into the food tissue or the fact that more preservative is present on the cut surface owing to coating thickness (Baldwin et al., 1996; Guilbert et al., 1996). This was demonstrated with a CMC/soy protein coating on cut potato with sorbate and benzoate (Baldwin et al., 1996).

### 2. Acidulants and pH Control Agents

The preservative effect of organic acids may be dependent on the pH resulting from their addition. However, different acids have different inhibitory effects at the same pH; thus the undissociated molecule also may play a role in addition to the hydrogen ion concentration (pH) (Doores, 1990; Kabara and Eklund, 1991). Acetic, lactic, propionic, fumaric, and citric acids can be used alone or in coatings to provide antimicrobial activity. Use of coatings with acidulants to establish a surface pH that favors the active form of sorbic acid and other preservatives is also a possibility (Torres and Karel, 1985). Acidulants can also be used in coatings to reduce pH on the commodity surface to retard browning, as was demonstrated with coated lychees (McGuire and Baldwin, 1996).

## B. Fumigation and Gas Treatments

Based on its oxidative properties (Davidson and Juneja, 1990), hydrogen peroxide is useful as an antibacterial agent that is effective at concentrations from 0.01% to 0.1%. It is especially effective against gram-negative bacteria such as coliforms. It is reportedly effective as a vapor-phase treatment fumigant for fresh table grapes but was not effective on melons. Previously, fumigation with sulfur dioxide was used, but, as with sulfites, there are concerns about adverse effects on some sensitive individuals (Forney et al., 1991).

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Nitrogen trichloride fumigation was used commercially on melons (Barger et al., 1948). Acetaldehyde vapor (0.05 to 0.5%) significantly reduced decay of harvested strawberries (Pesis and Avissar, 1990) and table grapes (Avissar and Pesis, 1991), while acetic acid vapor fumigation reduced fungal decay of grapes, apples, oranges, tomatoes, strawberries, and stone fruit (Moyls et al., 1996; Sholberg and Gaunce, 1995, 1996).

Other natural fruit and plant volatiles have been found to exhibit fungistatic activity. Of these volatiles, benzaldehyde, methyl salicylate, ethyl benzoate, hexanal, 1-hexanol, *trans*-2-hexenal 2-nonanone, and furan compounds were found to be particularly effective (Hardin, 1993; Song et al., 1996; Vaughn and Ehlenfeldt, 1993; Vaughn et al., 1993; Wilson et al., 1987).

The antimicrobial activity of $CO_2$ is greatest against molds and gram-negative psychrotrophic bacteria in the concentration range of 10% to 100% (Barkai-Golan, 1990; Davidson and Juneja, 1990) The mechanism of action is not known but may be related to lack of $O_2$, acidification of intracellular contents or effect on enzymes (Daniels et al., 1985). Various concentrations of $CO_2$ used in MAP are often within the microbialstatic range (Brody, 1996; Church and Parsons, 1995). High $CO_2$ (10% to 30%, sometimes in combination with low $O_2$) suppressed decay of strawberries (El-Neshawy et al., 1993; Harris and Harvey, 1973; Ke et al., 1991), blueberries (Converse, 1987), raspberries (Goulart et al., 1992), asparagus spears (Barkai-Golan, 1990; Lipton, 1964), spinach leaves (Babic and Watada, 1996), and cut endive (Bennik et al., 1996). However, $CO_2$ levels of 15% to 30% can cause injury in susceptible commodities. This was indicated by off flavors for strawberry (Harris and Harvey, 1973; Ke et al., 1991) and cucumber (Mencarelli, 1987), pitting of asparagus spears (Lipton, 1964), and browning of lettuce (Siriphanich and Kader, 1985).

## IV. ANTI-BROWNING TREATMENTS

Antioxidants are compounds that inhibit or prevent the oxidation reactions caused by free radicals, with or without oxidation enzymes, that cause discoloration or browning of certain fruit and vegetable tissues and rancidity of fats (Sapers, 1993; Sherwin, 1990). This can affect the color or flavor of mushrooms and fruit and vegetable products.

### A. Phenolic Antioxidants

The phenolic structure of certain compounds suppresses free radical formation, which delays the auto-oxidative process in fat or oil by acting as a proton donor (Sherwin, 1990). Approved phenolic antioxidants include butylated hydroxyanisole (BHA), butylated hydroxytoluene (BHT), esters of gallic acid such as propyl gallate, and *tert*-butyl hydroquinone (TBHQ). Natural antioxidants are also effective, such as the tocopherols and lecithin. The antioxidants BHA, BHT, tocopherol, and lecithin are GRAS, while TBHQ is approved as a direct food additive, and propyl gallate as an indirect food additive and component of coatings. Coatings have been used as carriers of antioxidants to retard rancidity of meat and nut products and discoloration of fresh-cut fruits and vegetables (Baker et al., 1994; Baldwin et al., 1996; Hoover and Nathan, 1981; Swenson et al., 1953). Antioxidants such as BHT have also been shown to affect changes in lipid classes in relation to chilling injury of cucumber (Geduspan and Peng, 1987).

### B. Other Antioxidants and Chelators

Some agents such as cinnamic and benzoic acids (both GRAS) are effective browning inhibitors in combination with ascorbic acid, since, like sulfites, they inhibit polyphenol

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oxidase (PPO) activity (Sapers et al., 1989). This enzyme is responsible for the browning that occurs when monophenolic compounds of plants are hydroxylated to *o*-diphenols and subsequently to *o*-quinones in the presence of $O_2$. The PPO enzyme requires copper; thus complexing and chelating agents such as ethylenediamine tetraacetic acid (EDTA) and citric acid can inhibit enzymatic browning (Sapers, 1993).

Ascorbic acid and its derivatives—erythorbic acid, ascorbic acid-2-phosphate and ascorbic acid-triphosphate—are effective inhibitors of enzymatic browning for cut apple (Sapers et al., 1991, 1989). Ascorbyl palmitate, cinnamic acid, benzoic acid, and β-cyclodextrin were reported to be effective browning inhibitors in juice (Sapers et al., 1989). Ascorbic acid, erythorbic acid, and ascorbyl palmitate are GRAS while the other ascorbic acid derivatives are not yet approved.

The amino acid cysteine is also an effective inhibitor of PPO (Richard et al., 1991) by reacting with quinone intermediates as well as reduced glutathione. Rosemary extract (and its constituents carnosol, carnosic acid, and rosmarinic acid) is a source of natural antioxidants (Frankel et al., 1996; Lai et al., 1991). Citric acid and EDTA have been incorporated into coatings as browning inhibitors for cut apples, potato, and mushrooms (Baldwin et al., 1996; Nisperos et al., 1991). Inorganic halides such as sodium or calcium chloride ($CaCl_2$) inhibit PPO (Sapers, 1993). A combination of erythorbate, cysteine, and EDTA helped to control browning in fresh-cut mushrooms (Sapers et al., 1994). Resorcinol and its derivatives, such as 4-hexylresorcinol, inhibit tyrosinase isozymes in mushrooms that cause browning and may inhibit PPO by serving as a substrate for this enzyme. In addition, resorcinol has antimicrobial activity (Monsalve-Gonzalez et al., 1995), but is not yet approved for food use in the United States.

## V. MINERAL AND GROWTH REGULATOR TREATMENTS

### A. Calcium

The mineral calcium has many postharvest uses (Poovaiah, 1986). This ion may induce phosphorylation of membrane or other proteins that affect intracellular processes, stabilize membranes (Lester, 1995; Picchioni et al., 1996), and maintain cell-wall structure (Conway et al., 1992; Glenn et al., 1988). Calcium, as calcium lactate or $CaCl_2$ dips, infiltrations (0.1% to 1.0%), or preharvest foliar applications on whole fruit have been reported to increase fruit firmness for blueberry (Hanson et al., 1993) and strawberry (Garcia et al., 1996). At various concentrations, calcium also delayed the ripening, senescence, and/or decay of several fruits, including strawberry (Cheour et al., 1991; Garcia et al., 1996) and muskmelon (Lester, 1995) and vegetables such as tomato (Wills and Tirmazi, 1977; 1979), potato (Conway et al., 1992; Conway et al., 1994), and mushroom (Barden et al., 1990). Treated cucumber fruit showed changes in lipid classes due to $CaCl_2$ treatment, which may have counteracted chilling injury–induced damage to membranes (Geduspan and Peng, 1987). Application of $CaCl_2$ with antioxidants reduced browning of parsnips (Toivonen, 1992) and calcium treatment inhibited russet spotting in lettuce (Ke and Salveit, 1986). Use of surfactants, as with chlorine, may enhance uptake of calcium and the effectiveness of calcium treatments (Roy et al., 1996).

Calcium has also benefited fresh-cut and processed fruits and vegetables by enhancing firmness, delaying senescence, and reducing discoloration. This has been reported for shredded carrots (Picchioni et al., 1996), sliced zucchini (Izumi and Watada, 1995), and sliced strawberry (Rosen and Kader, 1989). An edible coating containing $CaCl_2$

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along with antioxidants reduced browning of cut potato (Baldwin et al., 1996). Calcium application affected membrane-related lipid changes in shredded carrots, perhaps by minimizing injury due to processing (Picchioni et al., 1996). Addition of $CaCl_2$ to irrigation water improved postharvest quality and shelf life of mushrooms, in part by increasing levels of 1-octen-3-ol, an important volatile compound for this commodity (Mau et al., 1993).

Suggested reasons for the benefits of calcium application include alleviating disorders resulting from calcium deficiency, inhibition of ethylene production (Lieberman and Wang, 1982; Wang et al., 1993), effect of calcium on cell walls that makes them more resistant to decay (Conway et al., 1992; 1994) and firmer in texture, and adversely affecting conidial germination and germ-tube elongation (McLaughlin, 1990). Calcium may also affect activity of cell wall–digesting enzymes (Conway et al., 1992). Generally, levels of calcium must be higher to inhibit decay than required for other postharvest benefits. For example, apples inoculated with *Botrytis cinerea* Pers:Fr. were protected from decay by a 2% $CaCl_2$ dip (Klein et al., 1997), and strawberry fruit were protected from postharvest decay by a 1% dip (Garcia et al., 1996).

Calcium application has been reported to alter gas diffusion and thus the exchange of $CO_2$ and $O_2$ between fruit tissue and the outside atmosphere (Rajapakse et al., 1992). Calcium chloride has also been reported to aid in reduction of browning by inhibiting PPO (Sapers, 1993), which has been demonstrated for potatoes (Mazza and Qi, 1991).

## B. Growth Regulators

Growth regulator treatments can affect ripening- and senescence-related events. The most widely used hormone for treatment of fruits and vegetables is ethylene, a gaseous plant growth regulator that promotes abscission and ripening (Wills et al., 1998; Lurssen, 1991). Ethylene has been used commercially to enhance and coordinate ripening of tomatoes (Hobson and Grierson, 1993), peppers, and melons (Lurssen, 1991). Ethephon or Ethrel [(2-chloroethyl)phosphoric acid] is an aqueous formulation that decomposes to ethylene. Ethephon is used commercially to maximize once-over harvesting yields for tomatoes destined for processing (Farag and Palta, 1993). A natural lipid, lysophosphatidylethanolamine (LPE), also accelerated ripening of tomato fruit when sprayed in the field without the defoliation that often accompanies use of ethephon (Farag and Palta, 1993).

Ethylene production and thus ripening was shown to be inhibited in tomato by ethanol (Kelly and Salveit, 1988; Saltveit and Mencarelli, 1988) as well as by other ethylene synthesis and ethylene action inhibitors such as aminoethoxyvinylglycine (AVG) (Kende et al., 1980; Lieberman et al., 1975), silver ions, and 2,5-norbornadiene (Liu et al., 1989; Tucker and Brady, 1987). A new commercial product called ReTain™ (Abbott Laboratories, North Chicago, IL), whose active ingredient is AVG, is approved for preharvest use to reduce preharvest fruit drop, delay harvest, and enhance fruit storageability for apple (Abbot Laboratory Technical Summary). Undesirable effects of ethylene are shortened shelf life due to enhanced ripening or senescence and russet spotting in lettuce associated with induced phenylalanine ammonia-lyase (PAL) activity (Ke and Saltveit, 1988).

Methyl jasmonate, which promotes leaf senescence, stimulated ethylene in tomato while inhibiting lycopene synthesis (Saniewski and Czapski, 1985) and enhancing PPO activity (Czapski and Saniewski, 1988). It was also reported to reduce chilling injury of bell pepper (Meir et al., 1996) and zucchini squash, possibly by maintaining higher levels

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of spermidine and spermine during storage. Normally these compounds decrease during storage of zucchini (Butta et al., 1996; Wang, 1994).

Other growth regulators are antisenescent, such as cytokinins, gibberellins, auxins, and some polyamines. Cytokinins, such as $N^6$-benzyladenine, are usually applied preharvest or sometimes as postharvest dips (2 to 10 $\mu g\ L^{-1}$) (Halvey and Wittwer, 1966; Salunkhe and Wu, 1974; Zink, 1961). Cytokinin treatment delays chlorophyll breakdown, senescence, and sometimes water loss in lettuce, spinach, endives, and mustard greens as well as peppers, beans, cucumbers, cauliflower, parsley, snap beans, radishes, Brussels sprouts, broccoli (Dedolph et al., 1962), celery (Wittwer et al., 1962), and asparagus. Gibberellic acid (GA) was shown to retard ripening of tomato (Kader et al., 1966), but the effect was not uniform throughout the fruit. Postharvest treatment of celery with $GA_3$ inhibited decay by altering concentrations of phytoalexins associated with celery resistance to pathogens (psoralens) (Afek et al., 1994). The synthetic auxin, 2,4-dichlorophenoxy acetic acid (2,4-D), inhibited russet spotting in lettuce and associated PAL activity (Ke and Saltveit, 1986).

The polyamines spermine and spermidine increased firmness in sliced strawberry (Ponappa et al., 1993). Gibberellic acid ($GA_3$) inhibited ripening of strawberry (Martinez et al., 1994, 1996) and tomato (Dostal and Leopold, 1967) while auxin (*a*-naphthaleneacetic acid) enhanced growth of strawberry receptacles (Ponappa and Miller, 1996). Preharvest application of $GA_3$ (9 to 17 $gha^{-1}$) improved upright growth of spinach by increasing petiole length, and enhanced postharvest quality by reducing the percentage of unmarketable leaves (Johnson et al., 1989). This growth regulator is registered for preharvest application for several horticultural crops, including spinach. Tomato plants treated with GA before floral initiation developed tomatoes with more locules than controls (Sawhney and Dabbs, 1978), while tomatoes dipped in $10^{-5}$ to $10^{-3}$ M 2,4-D exhibited increased respiration, elevated ethylene production, and accelerated ripening. Tomato pericarp discs, however, showed delayed ripening in response to 2,4-D (Vendrell, 1985). Tomatoes grown from flowers in culture with $10^{-4}$ M indole-3-acetic acid (IAA) added to the medium resulted in parthenocarpic fruit. When additional IAA was added to the media before the fruit reached breaker stage, the fruit exhibited delayed ripening (Cohen, 1996). This confirmed earlier studies where IAA, potassium gibberellate, and kinetin extended the ripening period of tomatoes (Kader et al., 1966).

Experimental hormonal treatments have been applied to vegetables either as preharvest sprays or postharvest dips. Various growth retardants have been shown to have effects on harvested vegetables. Alar (succinamic acid, 2,2-dimethylhydrazide), which delays onset of ethylene production and prevents premature fruit drop in apples, accelerated ethylene production and ripening in tomatoes (Karam and Murr, 1980). Cycocel (2-chloroethyltrimethylammonium chloride), a GA inhibitor, retarded senescence of lettuce, broccoli, and asparagus (Halevy and Wittwer, 1966; Salunke and Wu, 1974). Abscisic acid (ABA), applied at $3 \times 10^{-5}$ to $10^{-3}$ M, was effective in reducing chilling injury of zucchini (Buta et al., 1996; Wang, 1991) and accelerated ripening of tomato (Kader et al., 1973; Mizrahi et al., 1975).

Growth regulators can also inhibit greening, solanine synthesis, and sprouting from potato and other tubers. Alar, Cycocel, Ethrel, and MH-30 or maleic hydrazide (1,2-dihydropyridazine-3,6-dione) inhibited chlorophyll and solanine formation induced by light in potato tubers (Patil et al., 1971). Gibberellic acid suppressed sprouting of yam tubers (Nnodu and Alozie, 1992). A review of reports from the 1950s and 1960s indicated that MH also inhibited sprouting of onions, radishes, sugar beets, turnips, and carrots either as preharvest or postharvest treatments (Salunke and Wu, 1974).

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## VI. ANTISPROUTING TREATMENTS

In addition to the above-mentioned growth regulators, inhibition of sprouting in potato tubers has been accomplished commercially using chlorpropham, or 1-methylethyl-3-chlorophenylcarbamate (CIPC). Partial control of light-induced glycoalkaloid formation has been accomplished with chemicals such as Ethephon and Alar as well as detergents and surfactants mentioned previously. Gamma-irradiation (1 to 2 kGy) has also shown promise (Salunkhe and Wu, 1979). Treatment of potatoes with CIPC also lowered total glycoalkaloid and ascorbic acid contents and increased phenolic content (Mondy and Ponnampalam, 1985; Ponnampalam and Mondy, 1986). Although this treatment has been used for decades, there has been concern over its toxicology. Apparently, CIPC is one of three pesticides found in highest concentrations in the American diet (Vaughn and Spencer, 1991). This has promoted efforts to find other, natural sprout inhibitors. Several naturally occurring monoterpenes, which are used as flavorings and in medications and perfumes, were found to be effective sprout inhibitors in the vapor phase. Of the compounds tested, 1,4-cineole, 1,8-cineole, and fenchone were most effective, followed by limonene oxide, linalool, and terpinen-4-ol (Vaughn et al., 1992b). In addition, some aromatic aldehydes and an alcohol also inhibited sprouting in vapor phase or when applied directly as emulsions (Vaughn et al., 1992a; Vaughn and Spencer, 1993). These compounds included salicylaldehyde, benzaldehyde, cinnamaldehyde, cuminaldehyde, and thymol.

## VII. QUARANTINE TREATMENTS

Fruit flies are major worldwide pests and their fruit hosts must be treated to kill 100% of the immatures inside fresh produce prior to export to uninfested areas of the world. A number of vegetables are hosts for fruit flies and other insect pests of quarantine concern. Currently available and potential quarantine treatments for vegetables were reviewed by Brecht (1994). One of the main treatments currently used, methyl bromide fumigation, is likely to be phased out over the next few years, since it is a suspected stratospheric ozone depleter. Other treatments available for fruits and vegetables include cold storage, hot air, vapor heat, and hot water treatments (Sharp and Hallman, 1994). Unfortunately, most of these treatments cause surface or internal quality damage to horticultural commodities. Recently, use of CA plus edible coatings has been investigated as an alternative treatment alone or in combination with currently used methods (Hallman, 1994; Hallman et al., 1994, 1995; Shellie et al., 1997). Preliminary findings suggest that lowered $O_2$ and elevated $CO_2$ within coated commodities may contribute to fruit fly mortality (Hallman et al., 1994, 1995). Fruit coatings are already approved as a disinfestation treatment for surface mites on cherimoyas and limes from South America (U.S. Department of Agriculture, 1993).

## VIII. CONCLUSION

Much progress has been made in the areas of postharvest physiology and technology, but there is room for much more. Tropical and subtropical products from warmer regions of the world are in great demand in northern latitudes, including the United States, Canada, and Europe. Currently, these commodities are often imported by air, which translates into high prices for the consumer. Unfortunately, the time required to transport fresh produce by sea or land results in high losses due to overripening and decay. Often produce is harvested immature or held at below optimum (chilling) temperatures in an attempt to

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prolong postharvest shelf life and therefore extend transport distances. This results in inferior quality at the retail market. Development of postharvest treatments to further extend fresh produce shelf life without sacrificing quality would greatly benefit the fresh produce industry and world trade in general.

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