Postharvest Pathology

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Introduction

Losses caused by postharvest diseases are greater than generally realized because the value of fresh fruits and vegetables increases several-fold while passing from the field to the consumer (Eckert and Sommer 1967). Postharvest losses are estimated to range from 10 to 30% per year despite the use of modern storage facilities and techniques (Harvey 1978).

Postharvest diseases affect a wide variety of crops, particularly in developing countries that lack sophisticated postharvest storage facilities (Jeffries and Jeger 1990). Infection by fungi and bacteria may occur during the growing season; at harvest time; during handling, storage, transport and marketing; or even after purchase by the consumer (Dennis 1983). Reduction of losses in perishable food crops resulting from postharvest diseases has become a major objective of international organizations (Kelman 1989). The reality is that there is a portending food crisis that will require the concerted efforts of all who are involved in food production to redouble their efforts. In fact, to adequately feed the world's expected 10 billion people within the next 40 to 50 years, food production efficiency and distribution will need to be improved immensely (Campbell 1998).

Specific causes of postharvest losses of fruits and vegetables may be classed as parasitic, nonparasitic, or physical (Cappellini and Ceponis 1984).This chapter deals with the parasitic causes that are of microbiological origin that begin as latent infections before harvest or occur at harvest or afterward during storage. Fungi are more commonly found attacking fruit, and bacteria are more common as postharvest pathogens of vegetables. This chapter will provide a general overview of the subject touching on noteworthy research where it can be used to illustrate postharvest pathology. The reader is encouraged to consult the references for specific information on the topics that are covered.

Factors that Influence Postharvest Pathology

Postharvest losses vary each year. Prevailing weather while the crop is growing and at harvest contribute greatly to the possibility of decay. Certain cultivars are more prone than others to decay caused by specific pathogens. In a recent study, it was found that resistance of major apple cultivars to the fungi that cause blue mold, gray mold, bull's-eye rot, and Mucor rot depended on cultivar (Spotts et al. 1999). Condition of the crop, as determined by fertilizer and soil factors, is very important in susceptibility of the crop to disease. Maturity of the crop at harvest, handling, and type of storage have great influence on how long the crop can be stored without decay. The following sections address how these preharvest factors lead to disease in specific crops.

Weather. Weather affects many factors related to plant diseases, from the amount of inoculum that overwinters successfully to the amount of pesticide residue that remains on the crop at harvest (Conway 1984). Abundant inoculum and favorable conditions for infection during the season often

result in heavy infection by the time the produce is harvested. For example, conidia of the fungus that causes bull's-eye rot are rain-dispersed from cankers and infected bark to fruit, especially if rainfall is prolonged near harvest time, resulting in rotten fruit in cold storage several months later (Spotts 1990).

Pinpoint or storage scab of apple caused by the same fungus that causes apple scab and gray mold caused by the fungus *Botrytis cinerea* are also very much influenced by the weather. Storage scab only occurs in years with unusually wet summers and early falls, when the fruit remain wet for a day or more. These late-season infections may not become visible until the apples are in storage (Pierson et al. 1971). Flowers and fruit are most vulnerable to *Botrytis cinerea* infection when conditions are wet. For example, in grapes infection occurs at 15 to 20 ºC (59 to 68 ºF) in the presence of free water after approximately 15 h (Bulit and Dubos 1988). In wet seasons, strawberries and raspberries may be harvested in apparently sound condition only to decay during transit and marketing (Snowdon 1990).

Postharvest decay involves further development of preharvest infections together with new infections arising from germination of spores on the fruit surface. From these examples it is apparent that decay often has a weather component, making thorough weather records an important source of information for predicting possible decay in storage.

Physiological Condition. Condition of produce at harvest determines how long the crop can be safely stored. For example, apples are picked slightly immature to ensure that they can be stored safely for several months. The onset of ripening and senescence in various fruit and vegetables renders them more susceptible to infection by pathogens (Kader 1985). On the other hand, fruit and vegetables can be made less prone to decay by management of crop nutrition. For example, calcium has been more closely related to disease resistance than any other cation associated with the cell wall (Sams 1994).

In a study on the effect of increased flesh calcium content of apples in storage, fruit were treated with solutions of $CaCl_2$ by dipping, vacuum, or pressure infiltration. Both vacuum and pressure infiltration increased calcium content of the fruit sufficiently to significantly reduce decay (Conway 1982). Increased calcium contents in potatoes and peaches have also been documented with reduced postharvest decay (Conway 1989). In general, produce containing adequate levels of calcium do not develop physiological disorders and can be stored longer before they breakdown or decay. Conversely, high nitrogen content in fruit predisposes them to decay (Conway 1984). In pears, it has been found that management of trees for low nitrogen and high calcium in the fruit reduced severity of postharvest fungal decay (Sugar et al. 1992). Apple cultivars can be selected for resistance to certain postharvest diseases (Spotts et al. 1999). For example, 'Royal Gala' is extremely resistant to wound pathogens, 'Granny Smith' to skin punctures, and 'Braeburn' to infiltration of fungal spores into the core.

Fungicide Sprays. Certain preharvest sprays are known to reduce decay in storage. Several studies done on the effectiveness of preharvest ziram fungicide application on pome fruit showed an average reduction in decay of about 25 to 50% with a single spray (Sugar and Spotts 1995). Iprodione has been used for several years as a preharvest spray 1 day before harvest to prevent infection of stone fruit by *Monilinia* spp. In combination with wax and/or oil, its decay control spectrum is increased and it will also control postharvest fungi such as *Rhizopus* and *Alternaria* (Ogawa et al. 1992). Several new fungicides that are being developed or that have recently been registered promise to protect produce from a number of diseases after harvest. For example, cyprodinil prevented gray mold infection in apple 3 months after it was applied (Sholberg and Bedford 1999). The new class of strobilurin fungicides promises to provide postharvest control of several diseases in fruits and vegetables, is

especially effective against fruit scab on apples, and should reduce the presence of pinpoint scab in storage.

Packing Sanitation. It is important to maintain sanitary conditions in all areas where produce is packed. Organic matter (culls, extraneous plant parts, and soil) can act as substrates for decay-causing pathogens. For example, in apple and pear packinghouses, the flumes and dump tank accumulate spores (Blanpied and Purnasiri 1968) and may act as sources of contamination if steps are not taken to destroy or remove them.

Chlorine readily kills microorganisms suspended in dump tanks and flumes if the amount of available chlorine is adequate. A level of 50 to 100 ppm of active chlorine provides excellent fungicidal activity (Spotts and Peters 1980). Chlorine measured as hypochlorous acid can be obtained by adding chlorine gas, sodium hypochlorite, or dry calcium hypochlorite. Though chlorine effectively kills spores in water, it does not protect wounded tissue against subsequent infection from spores lodged in wounds. Organic matter in the water inactivates chlorine, and levels of chlorine must be constantly monitored. The use of a sand filter in association with chlorination improves its efficiency probably because it removes organic matter (Sholberg and Owen 1990). Chlorine is sensitive to pH (Dychdala 1983): Hypochlorite solutions with higher pH values (7.5 to 8.5) are more stable but less fungicidal, whereas at lower pH values (5.5 to 6.5) the solutions are less stable but more fungicidal.

Recently, chlorine dioxide has replaced hypochlorite in some sanitizing processes, because several disadvantages limit the use of chlorine, including its unpleasant odor. Chlorine dioxide is not corrosive and is effective over a wide pH range (Spotts and Peters 1980). Recently in precisely controlled tests in water or as a foam, chlorine dioxide was found to be effective against common postharvest decay fungi on fruit packinghouse surfaces (Roberts and Reymond 1994). Peracetic acid is another material that could be used (Mari et al. 1999). It has greater stability and faster biocidal properties than chlorine dioxide but is more corrosive.

The search goes on for effective and economical sanitizing agents. New and old products alike are continually being evaluated under present-day packing operations. Interest in ozone has been rekindled with development of more efficient ozone generators. Acetic acid in the form of a gas is being evaluated for possible use as a sanitizing agent on several crops (Sholberg 1998). It was as effective as SO_2 in preventing gray mold decay in table grapes stored for 2 months (Sholberg et al. 1996).

Postharvest Treatments. Products or treatments used to control postharvest decay can be classified as either chemical or biological and should be selected only after proper consideration of the following conditions (Ogawa and Manji 1984):

- Type of pathogen involved in the decay
- Location of the pathogen in the produce
- Best time for application of the treatment
- Maturity of the host
- Environment during storage, transportation, and marketing of produce

Chemical Control

Several fungicides are currently used as postharvest treatments for control of a wide spectrum of

decay-causing microorganisms. However, when compared with preharvest pest-control products, the number is very small. Many products formerly used after harvest are no longer permitted because of concerns with residues and possible toxic effects, the most notable being products that contain benomyl. Other products are no longer as effective because of development of resistance by the target pathogen. For example, intensive and continuous use of fungicides for control of blue and green mold on citrus has led to resistance by the causal pathogens of these diseases (Eckert 1988). Resistance has been reported in many other crops to several different fungicides with different modes of action (Delp 1988). Resistance development continues to be a major problem and has resulted in the Fungicide Resistance Action Committee (FRAC), a cooperative effort among various producers of fungicides to delay resistance by recommending specific management guidelines (FRAC 1998).

Examples of chemicals currently used for postharvest treatments are thiabendazole, dichloran, and imazalil. However, resistance to thiabendazole and imazalil is widespread (Holmes and Eckert 1999), and their use as effective materials is declining. Preservatives or antimicrobial food additives are not generally thought of as postharvest treatments, but they do control decay and, in some cases, are the only means of control. These products include sodium benzoate, the parabens, sorbic acid, propionic acid, SO_2, acetic acid, nitrites and nitrates, and antibiotics such as nisin (Chichester and Tanner 1972). In California, for example, gray mold of stored table grapes is prevented by fumigation with SO_2 (Luvisi et al. 1992). The demand for new postharvest fungicide treatments is strong, especially since the loss of iprodione in 1996.

Fludioxinil was granted an emergency registration in 1998 to curb potential losses in nectarines, peaches, and plums (Forster and Adaskaveg 1999). Not all postharvest pathogens are currently controlled by materials that are available. For example, *Mucor piriformis*, a major postharvest pathogen of apples and winter pears in the Pacific Northwest is not controlled by any registered fungicide (Spotts and Dobson 1989). There is a dire need for new fungicide treatments that could in part be alleviated by using biological control agents (Wisniewski and Wilson 1992, Utkhede and Sholberg 1993).

Biological Control

Postharvest biological control is a relatively new approach and offers several advantages over conventional biological control (Wilson and Pusey 1985, Pusey 1996), such as the following:

- Exact environmental conditions can be established and maintained.
- The biocontrol agent can be targeted much more efficiently
- Expensive control procedures are cost effective on harvested food.

Several biological control agents have been developed in recent years, and a few have actually been registered for use on fruit crops. The first biological control agent developed for postharvest use was a strain of *Bacillus subtilis* (Pusey and Wilson 1984). It controlled peach brown rot, but when a commercial formulation of the bacterium was made, adequate disease control was not obtained (Pusey 1989). More recently, a strain of *Pseudomonas syringae* van Hall was found that controlled both blue and gray mold of pome fruit (Janisiewicz and Marchi 1992). It was subsequently registered and is now sold commercially for postharvest disease control (Janisiewicz and Jeffers 1997).

Other bacterial microorganisms are being developed for postharvest disease control. For example,

strains of *Bacillus pumilus* and *Pseudomonas fluorescens* have been identified that exhibit successful control of *B. cinerea* in field trials of strawberry (Swalding and Jeffries 1998). Yeasts such as *Pichia guilliermondii* (Wisniewski et al. 1991) and *Cryptoccocus laurentii,* which occur naturally on apple leaves, buds, and fruit (Roberts 1990), were the first to be applied for control of postharvest decay on fruit. The yeast *Candida oleophilia* has been registered for control of postharvest decay on fruit crops. The yeasts *Cryptococcus infirmo-minutus* and *Candida sake* successfully control brown rot and blue mold on sweet cherry (Spotts et al. 1998) and on three diseases of apple (Vinas et al. 1998), respectively, and may be developed commercially.

Though there is no doubt that biocontrols are effective, they do not always give consistent results. This could be because biocontrol efficacy is directly affected by the amount of pathogen inoculum present (Roberts 1994). Compatibility with chemicals used during handling is also important. Indications are that biological control agents must be combined with other strategies if they are to provide acceptable disease control.

Irradiation for Postharvest Decay Control

Though ultraviolet light has a lethal effect on bacteria and fungi that are exposed to the direct rays, there is no evidence that it reduces decay of packaged fruits and vegetables (Hardenburg et al. 1986). More recently, low doses of ultraviolet light irradiation (254 nm UV-C) reduced postharvest brown rot of peaches (Stevens et al. 1998). In this case, the low-dose ultraviolet light treatments had two effects on brown rot development: reduction in the inoculum of the pathogen and induced resistance in the host. However, it has not become a practical postharvest treatment as yet and requires more research.

Gamma radiation has been studied for controlling decay, disinfecting, and extending the storage life and shelf-life of fresh fruits and vegetables. Dosages of 1.5 to 2 kilograys (kGy) and, in some cases, 3.0 kGy (300 krad) have been effective in controlling decay in several products (Hardenburg et al. 1986). A dose of 250 grays (Gy) has an adverse effect on grapefruits, increasing skin pitting, scald, and decay. Low doses of 150 Gy for fruit flies and 250 Gy for codling moth are acceptable quarantine procedures (Meheriuk and Gaunce 1994). Commercial application of gamma radiation is limited by the cost and size of equipment needed for treatment and by uncertainty about consumers' acceptance of irradiated foods (Hardenburg et al. 1986). Gamma irradiation may be used more in the future once methyl bromide is no longer available to control insect infestation in stored products. All uses of methyl bromide are being phased out to avoid any further damage to the protective layer of ozone surrounding the earth.

Effect of Storage Environment on Postharvest Decay

Commercial producers and handlers modify temperature, RH, and atmospheric composition during prestorage, storage, and transit to control decay (Spotts 1984). For optimum decay control, two or more factors often are modified simultaneously.

Temperature and RH. Proper management of temperature is so critical to postharvest disease control that all other treatments can be considered as supplements to refrigeration (Sommer 1989). Fruit rot fungi generally grow optimally at 20 to 25 ºC (68 to 77 °F) and can be conveniently divided into those with a growth minimum of 5 to 10 ºC (41 to 50 °F) and those with a growth minimum of -6 to 0 ºC (21 to 32 °F). Fungi with a minimum growth temperature below -2 ºC (28 °F) cannot be

completely stopped by refrigeration without freezing the fruit. However, temperatures as low as possible are desirable because they significantly slow growth and thus reduce decay.

High temperature may be used to control postharvest decay on crops that are injured by low temperatures, such as mango, papaya, pepper, and tomato (Spotts 1984). Though hot water generally is more effective, hot air has been used to control decay in crops that are injured by hot water. Heating of pears at temperatures from 21 to 38 ºC (70 to 100 °F) for 1 to 7 days reduced postharvest decay (Spotts and Chen 1987). Decay in 'Golden Delicious' apples was reduced by exposure to 38 ºC (100 °F) for 4 days (Sams et al. 1993) and virtually eliminated when treated after inoculation (Fallik et al. 1995, Klien et al. 1997). Heat treatment eliminates incipient infections and improves coverage by fungicides (Couey 1989). The primary obstacle to the widespread use of heat to control postharvest fruit diseases or insect infestation is the sensitivity of many fruit to the temperatures required for effective treatment.

Both low and high RH have been related to postharvest decay control. Perforated polyethylene bags for fruit and vegetable storage create RH about 5 to 10% above that in storage rooms. Though shrivel and weight loss are reduced, decay may increase (Spotts 1984). Crops with well-developed cuticle and epidermis, such as apples and pears, tolerate lower RH levels, which helps prevent storage decay. Often fungal spore germination is inhibited at low RH, and small differences in RH can have significant effects in relation to the degree of postharvest decay (Spotts and Peters 1981).

Modified or Controlled Atmospheres. Alterations in O_2 and CO_2 concentrations are sometimes provided around fruit and vegetables (Spotts 1984). With close control of these gases, the synthetic atmosphere is commonly called a "controlled atmosphere"; the term "modified atmosphere" is used when there is little possibility of adjusting gas composition during storage or transportation (Sommer 1989). Because the pathogen respires as does produce, lowering O_2 or raising CO_2 above 5% can suppress pathogenic growth in the host. In crops such as stone fruits, a direct suppression occurs when fungal respiration and growth are reduced by the high CO_2 of the modified atmosphere. For example, CO_2 added to air has been widely used in the transport of 'Bing' cherries, primarily to suppress gray mold and brown rot. Low O_2 does not appreciably suppress fungal growth until the concentration falls below 2%. Important growth reductions result if O_2 is lowered to 1% or less, though there is a danger that the crop will start respiring anaerobically and develop off flavors. Other technologies that have been tested for lowering postharvest decay with limited success are storage and transport under low O_2 and the use of carbon monoxide (Spotts 1984, Sommer 1989).

Postharvest Diseases of Fruits

Fruit crops are attacked by a wide range of microorganisms in the postharvest phase (Snowdon 1990, Ogawa and English 1991). Actual disease only occurs when the attacking pathogen starts to actively grow in the host. Diseases are loosely classified according to their signs and symptoms. Signs are visible growths of the causal agents, and symptoms the discernible responses produced by the host. In many diseases there is local discoloration and disruption of tissue, with the formation of obvious lesions. Postharvest diseases are caused primarily by microscopic bacteria and fungi, with fungi the most important causal agent in fruit crops.

Fungi are further subdivided into classes and are described as "lower fungi" (characterized by the production of sporangia giving rise to numerous sporangiospores) or "higher fungi" (described as

ascomycetes, deuteromycetes, and basidiomycetes.) Ascomycetes are exemplified by fruiting bodies that release sexual spores when mature. Deuteromycetes, a form of ascomycete, only release asexual spores. They are more common than the sexual ascomycete stage in postharvest crops. Deuteromycetes are further subdivided into hyphomycetes and coelomycetes based on spore and structural characteristics. The agonomycetes contain important soil pathogens that form survival structures known as "sclerotia," which allow them to survive in the absence of the host. These fungi and the rust and smut fungi are examples of basidiomycetes. Table 1 lists many important diseases of fruit crops according to host and causal agents.

Table 1. Important postharvest diseases of fruit

Fruit	Disease	Causal agent	Fungal class/type
Avocado	Anthracnose	*Glomerella cingulata*	Pyrenomycete
	Cercospora spot	*Pseudocercospora purpurea*	Hyphomycete
	Dothiorella rot	*Botryosphaeria ribis*	Loculoascomycete
	Scab	*Sphaceloma persae*	Coleomycete
	Stem-end rots	*B. theobromae, Phomopsis perseae, Thyronectria pseudotrichia*	Deuteromycetes
Banana	Anthracnose	*Colletotrichum musae*	Coelomycete
	Cigar-end rot	*Trachysphaera fructigena, Verticillium theobromae*	Deuteromycetes
	Crown rot	*C. musae, Fusarium pallidoroseum, V. theobromae*	Deuteromycetes
	Finger rot	*B. theobromae*	Coelomycete
	Pitting disease	*Pyricularia grisea*	Hyphomycete
	Sigatoka disease	*Mycosphaerella* spp.	Loculoascomycete
Berries	Gray mold	*Botrytis cinerea*	Hyphomycete
	Leak	*Mucor* spp.	Zygomycete
	Leather rot	*Phytophthora* spp.	Oomycete
Citrus	Alternaria rot	*Alternaria* spp.	Hyphomycete
	Anthracnose	*C. gloeosporioides*	Coelomycete
	Bacterial canker	*Xanthomonas campestris*	Bacterium
	Black pit	*Pseudomonas syringae*	Bacterium
	Black spot	*Phyllosticta citricarpa*	Coelomycete
	Blue mold	*Penicillium italicum*	Hyphomycete
	Brown rot	*Phytophthora* spp.	Oomycete
	Greasy spot	*Mycosphaerella citri*	Loculoascomycete
	Green mold	*P. digitatum*	Hyphomycete
	Scab	*Elsinoe fawcettii*	Loculoascomycete
	Sour rot	*Geotrichum candidum*	Hyphomycete
	Stem-end rots	*D. gregaria, Phomopsis citri,*	Coelomycete

		B. theobromae	
Kiwifruit	Gray mold	*B. cinerea*	Hyphomycete
Grape	Aspergillus rot	*Aspergillus niger*	Hyphomycete
	Blue mold	*Penicillium* spp.	Hyphomycete
	Gray mold	*B. cinerea*	Hyphomycete
	Rhizopus rot	*Rhizopus* spp.	Zygomycete
Mango	Anthracnose	*C. gloeosporioides*	Coelomycete
	Botryodiplodia rot	*B. theobromae*	Coelomycete
	Stem-end rots	*B. theobromae, Phomopsis* spp.	Coelomycete
Papaya	Anthracnose	*C. gloeosporioides*	Coelomycete
	Black rot	*Phoma caricae-papayae*	Coelomycete
	Phytophthora rot	*P. palmivora*	Oomycete
	Rhizopus rot	*R. stolonifer*	Zygomycete
	Stem-end rot	*B. theobromae, Phomopsis* spp.	Coelomycete
Pineapple	Black rot	*Thielaviopsis paradoxa*	Hyphomycete
	Fruitlet core rot	*Fusarium moniliforme, P. funiculosum*	Hyphomycete
Pome fruit (apple, pear)	Bitter rot	*C. gloeosporioides*	Coelomycete
	Black rot	*Sphaeropsis malorum*	Coelomycete
	Blue mold	*Penicillium expansum, Penicillium* spp.	Hyphomycete
	Brown rot	*Monilinia* spp.	Hyphomycete
	Bull's-eye rot	*Cryptosporiopsis curvispora*	Hyphomycete
	Gray mold	*B. cinerea*	Hyphomycete
	Moldy core	*Alternaria* spp., others	Hyphomycete
	Mucor rot	*Mucor piriformis*	Zygomycete
	White rot	*D. gregaria*	Coelomycete
Stone fruit (cherry, etc.)	Alternaria rot	*A. alternata*	Hyphomycete
	Blue mold	*P. expansum*	Hyphomycete
	Brown rot	*Monilinia* spp.	Hyphomycete
	Rhizopus rot	*Rhizopus* spp.	Zygomycete

Postharvest Diseases of Vegetables

Postharvest diseases of vegetables are caused by microscopic fungi and bacteria (Snowdon 1992, Howard et al. 1994). Bacteria are more common as pathogens of vegetables than fruit because, in general, vegetables are less acidic than fruit. Bacteria are visible under the light microscope as mostly single-celled rods. Bacteria are capable of very rapid multiplication under the right conditions of pH,

temperature, and nutrition. They are classified according to their size, shape, reaction to certain stains, and behavior on various growth media (Krieg and Holt 1984). The term "vegetable" encompasses a range of plant parts, and the common definition is a culinary one, denoting consumption as a savory rather than as a dessert food (Snowdon 1992). Many vegetables are fruits in the botanical sense, notable examples being tomatoes, peppers, squashes, and cucumbers. Table 2 lists many of the important diseases of vegetable crops according to host and causal agents.

Table 2. Important postharvest diseases of vegetables

Vegetable	Disease	Causal Agent	Fungal Class/Type
Bulbs	Bacterial soft rot	*Erwinia caratovora*	Bacterium
(onion, garlic)	Black rot	*Aspergillus niger*	Hyphomycete
	Blue mold rot	*Penicillium* spp.	Hyphomycete
	Fusarium basal rot	*Fusarium oxysporum*	Hyphomycete
	Neck rot	*Botrytis* spp.	Hyphomycete
	Purple blotch	*Alternaria porri*	Hyphomycete
	Sclerotium rot	*Sclerotium rolfsii*	Agonomycete
	Smudge	*Colletotrichum circinans*	Coelomycete
Crucifers	Alternaria leaf spot	*Alternaria* spp.	Hyphomycete
(cabbage, etc.)	Bacterial soft rot	*E. caratovora*	Bacterium
	Black rot	*Xanthomonas campestris*	Bacterium
	Downy mildew	*Peronospora parasitica*	Oomycete
	Rhizoctonia rot	*Rhizoctonia solani*	Agonomycete
	Ring spot	*Mycosphaerella brassicicola*	Loculoascomycete
	Virus diseases	Cauliflower mosaic virus, turnip mosaic virus	Virus
	Watery soft rot	*Sclerotinia* spp.	Discomycete
	White blister	*Albugo candida*	Oomycete
Cucurbits	Anthracnose	*Colletotrichum* spp.	Coelomycete
(cucumber, etc.)	Bacterial soft rot	*Erwinia* spp.	Bacterium
	Black rot	*Didymella bryoniae*	Loculoascomycete
	Botryodiplodia rot	*Botryodiplodia theobromae*	Coelomycete
	Charcoal rot	*Macrophomina phaseolina*	Coelomycete
	Fusarium rot	*Fusarium* spp.	Hyphomycete
	Leak	*Pythium* spp.	Oomycete
	Rhizopus rot	*Rhizopus* spp.	Zygomycete
	Sclerotium rot	*Sclerotium rolfsii*	Agonomycete
	Soil rot	*R. solani*	Agonomycete
Legumes	Alternaria blight	*A. alternata*	Hyphomycete
(peas, beans)	Anthracnose	*Colletotrichum* spp.	Coelomycete
	Ascochyta pod spot	*Ascochyta* spp.	Coelomycete
	Bacterial blight	*Pseudomonas* spp., *Xanthomonas* spp.	Bacteria
	Chocolate spot	*B. cinerea*	Hyphomycete
	Cottony leak	*Pythium* spp.,	Oomycete

		Mycosphaerella blight, *M. pinodes*	Loculoascomycete
	Rust	*Uromyces* spp.	Hemibasidiomycete
	Sclerotium rot	*S. rolfsii*	Agonomycete
	Soil rot	*R. solani*	Agonomycete
	White mold	*Sclerotinia* spp.	Discomycete
Roots/tubers			
Carrots	Bacterial soft rot	*Erwinia* spp., *Pseudomonas* spp.	Bacteria
	Black rot	*A. radicina*	Hyphomycete
	Cavity spot	Disease complex	Soil fungi
	Chalaropsis rot	*Chalara* spp.	Hyphomycete
	Crater rot	*R. carotae*	Agonomycete
	Gray mold rot	*B. cinerea*	Hyphomycete
	Sclerotium rot	*S. rolfsii*	Agonomycete
	Watery soft rot	*Sclerotinia* spp.	Discomycete
Potatoes	Bacterial soft rot	*Erwinia* spp.	Bacteria
	Blight	*Phytophthora infestans*	Oomycete
	Charcoal rot	*S. bataticola*	Agonomycete
	Common scab	*Streptomyces scabies*	Actinomycete
	Fusarium rot	*Fusarium* spp.	Hyphomycete
	Gangrene	*Phoma exigua*	Coelomycete
	Ring rot	*Clavibacter michiganensis*	Bacterium
	Sclerotium rot	*S. rolfsii*	Agonomycete
	Silver scurf	*Helminthosporium solani*	Hyphomycete
	Watery wound rot	*Pythium* spp.	Oomycete
Sweet potatoes	Black rot	*Ceratocystis fimbriata*	Pyrenomycete
	Fusarium rot	*Fusarium* spp.	Hyphomycete
	Rhizopus rot	*Rhizopus* spp.	Zygomycete
	Soil rot	*Streptomyces ipomoeae*	Actinomycete
	Scurf	*Monilochaetes infuscans*	Hyphomycete
Solanaceous plants (tomato, pepper, eggplant)	Alternaria rot	*A. alternata*	Hyphomycete
	Anthracnose	*Colletotrichum* spp.	Coelomycete
	Bacterial canker	*C. michiganensis*	Bacterium
	Bacterial speck	*Pseudomonas syringae*	Bacterium
	Bacterial spot	*X. campestris*	Bacterium
	Fusarium rot	*Fusarium* spp.	Hyphomycete
	Gray mold rot	*B. cinerea*	Hyphomycete
	Late blight	*P. infestans*	Oomycete
	Phoma rot	*Phoma lycopersici*	Hyphomycete
	Phomopsis rot	*Phomopsis* spp.	Coelomycete
	Phytophthora rot	*Phytophthora* spp.	Oomycete
	Pleospora rot	*Stemphylium herbarum*	Hyphomycete
	Rhizopus rot	*Rhizopus* spp.	Zygomycetes
	Sclerotium rot	*S. rolfsii*	Agonomycete
	Soil rot	*R. solani*	Agonomycete

	Sour rot	*Geotrichum candidum*	Hyphomycete
	Watery soft rot	*Sclerotinia* spp.	Discomycete
Miscellaneous			
Artichokes	Gray mold	*Botrytis cinerea*	Hyphomycete
	Watery soft rot	*Sclerotinia sclerotiorum*	Discomycete
Asparagus	Bacterial soft rot	*Erwinia* or *Pseudomonas* spp.	Bacteria
	Fusarium rot	*Fusarium* spp.	Hyphomycete
	Phytophthora rot	*Phytophthora* spp.	Oomycete
	Purple spot	*Stemphylium* spp.	Hyphomycete
Celery	Bacterial soft rot	*Erwinia* or *Pseudomonas* spp.	Bacteria
	Brown spot	*Cephalosporium apii*	Hyphomycete
	Cercospora spot	*Cercospora apii*	Hyphomycete
	Gray mold	*Botrytis cinerea*	Hyphomycete
	Licorice rot	*Mycocentrospora acerina*	Hyphomycete
	Phoma rot	*Phoma apiicola*	Coelomycete
	Pink rot	*Sclerotinia* spp.	Discomycete
	Septoria spot	*Septoria apiicola*	Coelomycete
Lettuce	Bacterial rot	*Erwinia, Pseudomonas, Xanthomonas* spp.	Bacteria
	Gray mold rot	*B. cinerea*	Hyphomycete
	Rhizoctonia rot	*R. solani*	Agonomycete
	Ringspot	*Microdochium panattonianum*	Hyphomycete
	Septoria spot	*S. lactucae*	Coelomycete
	Stemphylium spot	*Stemphylium herbarum*	Hyphomycete
	Watery soft rot	*Sclerotinia* spp.	Discomycete

New Directions for Postharvest Plant Pathology

Postharvest plant pathology has changed its emphasis in the last decade. Food safety has emerged as a key element in decay control programs. Continued failure to effectively control certain postharvest diseases and the need for more environmentally friendly crop control materials require a new approach to disease control. Integrated postharvest decay control is the concept that offers the most promise for the future. Society can no longer rely on one or two control strategies but must enlist the entire spectrum of strategies to reduce postharvest losses.

Food Safety Issues

The two most important causes of unsafe food are microbial toxins (Hsieh and Gruenwedel 1990) and contamination of horticultural products by fecal coliforms (Gould 1973). The microbial toxins can be subdivided into bacterial toxins and toxins produced by fungi or mycotoxins. An example of a

microbial toxin that is extremely toxic are the botulinum toxins produced by the anaerobic bacterium *Clostridium botulinum*.

Interest in toxins produced by fungi was stimulated by the death of 100,000 turkey poults in England in 1960. Aflatoxins produced by fungi in the peanut meal used to feed the birds was the cause. Studies have since shown aflatoxins to be potent carcinogens that may occur in nuts and grain (Phillips 1984, Ellis et al. 1991). Other toxins have been identified that are produced by the same fungi that cause postharvest decay. For example, patulin produced by *Penicillium* and *Aspergillis* spp. can be found in apple and pear products. Patulin is toxic to many biological systems but its role in causing animal and human disease is unclear (Hsieh and Gruenwedel 1990).

Studies on contamination of horticultural products by fecal coliforms has increased dramatically because of documented incidences of food poisoning from apple juice and seed sprouts. Definite interactions have been shown between plant pathogens and foodborne human pathogens such as *Salmonella* and *Listeria*. A study involving more than 400 samples each of healthy and soft-rotted commodities collected in retail markets indicated that the presence of *Salmonella* on produce affected by bacterial soft rot was twice that of healthy samples (Wells and Butterfield 1997). Controlled experiments with potato, carrot, and pepper tissues inoculated with a strain of *Salmonella* confirmed that bacterial soft rot infection increased multiplication of *Salmonella* by at least three- to ten-fold compared with multiplication on uninfected tissues. Similarly, populations of *Listeria monocytogenes,* inoculated into decayed apple tissue, continually increased on fruit decayed by *Glomerella cingulata* but did not survive after 5 days on fruit decayed by *Penicillium expansum* (Conway et al. 2000). The pH of the decayed area declined from pH 4.7 to 3.7 in the case of *P. expansum* but increased from pH 4.7 to 7.0 in the case of *G. cingulata*. This pH modification may be responsible for affecting growth of the foodborne pathogen.

Contamination of produce with human pathogens is an important issue that must be addressed along with limiting decay caused by postharvest pathogens and maintaining product quality.

Integrated Control of Postharvest Diseases

Effective and consistent control of storage diseases depends on integration of the following practices:

- Select disease-resistant cultivars where possible.
- Maintain correct crop nutrition by use of leaf and soil analysis.
- Irrigate based on crop requirements and avoid overhead irrigation.
- Apply preharvest treatments to control insects and diseases.
- Harvest crop at the correct maturity for storage.
- Apply postharvest treatments to disinfest and control diseases and disorders on produce.
- Maintain good sanitation in packing areas and keep dump-water free of contamination.
- Store produce under conditions least conducive to growth of pathogens.

Integration of cultural methods and biological treatments with yeast biocontrols has been studied on pears (Sugar et al. 1994). It was found that early harvest, low fruit nitrogen, high fruit calcium, yeast or yeast plus fungicide treatment, and controlled atmosphere storage all reduced severity of blue mold and side rot. These results demonstrated that unrelated cultural and biological methods that influenced pear decay susceptibility can be combined into an integrated program to substantially reduce decay.

In another example of an integrated strategy, 'Gala' apples were heat-treated at 38 ^{o}C (100 °F) for 4 days, followed by calcium infiltration with 2% $CaCl_2$, and then treated with the microbial antagonist, *Pseudomonas syringae* (Conway et al. 1999). The combined strategy was much more effective than any single strategy for two reasons. First, heat treatment reduced the pathogen population on the fruit surface but did not provide any residual protection. Second, the residual protection was provided by calcium, and the biocontrol agent added to the control provided by the heat treatment.

As a general rule, alternatives to chemical control are often less effective than many fungicides. It is highly unlikely that any one alternative method alone will give the same level of control as fungicides. Therefore, it will generally be necessary to combine several alternative methods to develop an integrated strategy to successfully reduce postharvest decay.

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