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Sales of Vegetables for Fresh Market: The Requirement for Hazard Analysis and Critical Control Points (HACCP) and Sanitation

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I. INTRODUCTION

Vegetables displayed in modern markets are bright, clean and, above all, attractive. Foreign matter, soil, decay, and visible chemical residues are absent, since the presence of such material would profoundly influence consumers' willingness to buy the product. A fresh vegetable's value in the market is also affected by consumers' concerns that an invisible hazard might be present. Two general procedures, a Hazard Analysis and Critical Control Points (HACCP) system and sanitation, can help the fresh vegetable industry allay consumers' fears about fresh fruits and vegetables.

II. HAZARD ANALYSIS AND CRITICAL CONTROL POINTS

Hazard analysis and critical control points (HACCP), which was originally developed for the National Aeronautics and Space Administration (NASA) space program, represents a systematic process for reducing visible and invisible contaminants of food. HACCP is focused totally on food safety. HACCP employs formalized criteria for reducing the chances that biological, chemical, or physical hazards will contaminate the final product. Specifically, ''HA'' is an analysis of hazards that could contaminate the product and ''CCP'' represents steps in the product flow where hazards can be controlled.

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The food canning industry has used HACCP for more than 20 years. Relatively few serious outbreaks of illness have been associated with canned products during that period. Many other food processors have employed aspects of HACCP but have not formalized their food safety activities. New regulations from the U.S. Department of Agriculture (USDA) and the Food and Drug Administration (FDA) require processors of meat, poultry, and seafood to produce their products under a HACCP system. In the near future, HACPP will likely be required of other segments of the food industry, including institutional and commercial food services, and increasingly of producers and processors of foods that are consumed raw.

A. Creating a HACCP System

HACCP must be carefully planned before it can be successfully implemented. Company personnel usually develop the program and make certain that each provision is carried out correctly. Third-party consultants may be called in periodically to verify and validate the system. Personnel developing the plan should be aware of HACCP theory; at least one should have received specific training. The planning team should be completely familiar with their company's products, including how each one is handled, shipped, stored, marketed, and used by the final consumer. The team should predict how the product might be abused and then evaluate the probable consequences of that abuse. At least one member of the planning team should have fundamental knowledge of the likely hazards, including what, why, sources, detection, and hazard dynamics in product. Hazard dynamics are particularly important, since those likely to increase in intensity during normal storage and marketing are of greater concern than those that remain stable, decrease, or even disappear.

The HACCP system adopted by a fresh vegetable company must be compatible with product flow, essential handling processes, and business profitability. Companies producing several vegetable products may require multiple HACCP systems. Single systems can be applied to all products sharing the same basic processes.

B. HACCP Principles

The seven principles of HACCP are illustrated below for a grower of fresh vegetables. The grower was selected for this illustration because growing the crop is the first essential step in marketing a vegetable. Vegetables that become contaminated in the field or during harvest are likely to remain so. As noted by Fain (1994), there are no reliable means for decontaminating fresh produce.

The HACCP planning team begins by listing on a flow chart each production, handling, or processing step controlled by the company. A typical grower controls (a) where the crop will be planted (site selection); (b) site preparation; (c) planting of crop; (d) crop culture (includes irrigation, pest control, cultural practices such as thinning crop, training crop to trellis, etc.); (e) harvesting of crop; and (f) moving of harvested crop from field to packer or other receiver. After listing steps in the company's process flow, the HACCP team applies the seven principles of HACCP to that flow.

1. Identify Hazards and Their Control (HA)

Common hazards for fresh vegetables are contamination by physical, chemical, and microbial agents that might injure or offend consumers. Physical hazards include wounds and bruises on the product and foreign objects such as pieces of metal, rocks, glass, human

Table 1 Hazards Analysis and Control of Hazards for Vegetable Crop Production

Hazard	Sources	Critical control points
Escherichia coli	1. Raw manure 2. Fecal matter from domestic or wild animals 3. Polluted water 4. Workers 5. Contaminated equipment (containers, trucks, etc.)	Select proper field location, field design, fertilizer, fertilization method, water source, and irrigation method. Supervise workers with respect to hygiene as well as equipment use and cleanliness.

or animal hair, inset parts or frass, etc. Chemical hazards include fluids from machinery, cleaning agents, heavy metals, certain organic chemicals, toxins from certain fungi and bacteria, excessive pesticide residues, etc. Biological hazards include visible mold or bacterial growth, spoilage, or decay; bacteria, viruses, or parasites that cause human illness; bacteria that indicate probable fecal contamination; etc. As the planning team discusses each hazard, possible preventive measures are reviewed and listed beside the hazard.

In our example of a HACCP system for a vegetable producer, only contamination by agents responsible for human disease are considered. One of the more important of these biological hazards, *Escherchia coli* (see Chap. 21), is used in our example.

2. Identify Critical Control Points (CCPs)

The planning team next determines points in the product flow where hazards can be controlled or removed. The CCPs are steps where hazard control is essential, usually because later efforts will be ineffective. The effort and expense required to manage a CCP, however, can often be reduced by action taken prior to or after that point. For example, prompt cooling of tomatoes after harvest slows the development of postharvest pathogens as well as the ripening and senescence of the fruit. The slowing of pathogen activities and senescence of the tomatoes reduces the chances for decay development, thereby increasing the operation's tolerance of pathogen populations.

To prevent their crop from becoming contaminated by *E. coli*, the HACCP team decides to isolate the crop from potential sources of the bacterium (Table 1). Steps from selection of field location through supervision of workers are absolutely essential to prevent contact of crop with sources of *E. coli*. These ''absolutely essential steps'' represent CCPs.

3. Establish Critical Limits for Each CCP

Each CCP will have one or more critical limits that must be met to reduce the hazard to acceptable levels (Table 2). The critical limit of 5 mi as the minimum distance between

Table 2 Critical Limits at a CCP for *Escherichia coli* Hazard in Production of a Vegetable Crop

Hazard	CCP	Critical Limits
Escherichia coli	Field location	1. Field located at least 5 mi from nearest concentration of livestock (feedlot, dairy, or pasture). 2. Surround field with livestock-proof fence.

field and nearest concentration of livestock was arbitrary and is based on spread of plant pathogenic bacteria during severe storms (Gottwald et al., 1997). Severe storms can transport aerosols, leaf matter, rainfall, or debris containing bacteria more than 5 mi from the source. Although the numbers of bacteria dispersed 5 mi would likely be small, plant pathogens can survive and multiply on vegetables, particularly if introduced into wounds (see Chap. 21). Whether small numbers of *E. coli* deposited on plants by a storm could multiply is unknown, but unlikely based on current information (see Chap. 21). Thus, 5 mi to the nearest concentration of livestock appears to be a reasonable critical limit. Additionally, this distance should limit insect movement from manure to crop, an important consideration, since fruit flies have been shown capable of moving *E. coli* from contaminated apple fruit to wounds on noncontaminated fruit (Janisiewicz et al., 1988).

4. Establish Procedures for Monitoring CCPs

Periodic monitoring is necessary to ensure that critical limits are not being exceeded at each CCP. Monitoring also provides a degree of process control as well as data required for verification of the HACCP system. The HACCP team determines the frequency of monitoring and the most appropriate person to take this responsibility.

5. Establishing Corrective Actions for Violations of Critical Limits

Occasionally, critical limits will be exceeded. Most violations are likely to be minor and easily corrected. A few might make the crop hazardous to consume raw. The HACCP team establishes specific actions to be taken when limits are exceeded (Table 3). Each deviation is documented so that records can be maintained on the product for its expected life. The person is charge of the HACCP program must have the authority to take prompt corrective action when critical limits are exceeded.

6. Establish an Effective Documentation System

Records are kept on file to allow verification of the HACCP system as well as for need-driven evaluation of processing steps. HACCP records for small businesses might be kept in a logbook or diary, whereas larger businesses require more elaborate records. For all businesses, such records and evidence of third-party verification are extremely valuable in the event of legal action because of an outbreak of food-borne illness or an apparent violation of food safety regulations.

7. Verify That the HACPP System Is Working

The system should be verified at predetermined time intervals, as well as at times when hazards are likely to appear, to be certain that hazards are at acceptable levels. Verification includes making certain that critical limits are being met and that all parts of the HACCP system are functioning as originally designed in the HACCP plan. Provisions must be in place to ensure that the system will remain effective through changes in personnel, cultivars, weather, or technology. The HACCP personnel must be available for interactions with governmental regulatory agencies responsible for ensuring food safety. Additionally, the personnel must sample occasional products to check for physical, chemical, or microbiological hazards.

C. Desirability of HACCP Systems in the Fresh Vegetable Industry

Currently, the FDA does not require businesses involved in the production and marketing of fresh vegetables to implement HACCP systems. Whether this will change in the future

Table 3 Hazard, CCPs, Critical Limits, Monitoring Procedure, and Corrective Action

Process step and hazard	CCP	Critical limits	Monitoring procedure	Corrective action(s)
Growing crop—protect from contact with manure containing *E. coli*.	Isolate field from sources. Keep livestock or other animals from entering field.	1. Field at least 5 mi from nearest concentration of livestock and not adjacent to pasture. 2. Intact livestock proof fence surrounds field. 3. Adjacent fields not used for disposal of manure.	1. Check fence integrity. 2. Tour area around field. 3. Stay in contact with people using adjacent fields. 3. Test random samples of plants for fecal coliforms, particularly after storms.	1. Repair fence as necessary. 2. Determine areas of field contacted by animals; destroy plants that have been in direct contact with animals or fecal matter. 3. If fecal coliforms detected on plants at harvest, wash vegetables with chlorinated water and retest for coliforms using enrichment techniques. Alternatively, send product to cannery or other processor.

is unclear. Recent outbreaks of illness associated with fresh vegetables, particularly seed sprouts (see Chap. 21), increase the likelihood that HACCP systems will become required for certain products. However, the United Fresh Fruit and Vegetable Association noted on July 25, 1997, that use of the term *HACCP* for food safety programs focused on minimizing pathogen contamination was inappropriate due to a lack of scientific support (NACMCF, 1998). The organization preferred applying the terms *Good Agricultural Practices* and *Good Handling Practices*. By contrast, the International Fresh Cut Produce Association has proposed seven CCPs and found, in a 1997 membership survey, that 61% of the respondents had implemented a verified HACCP plan. Consumer confidence in fresh vegetables is best maintained through a demonstration by the industry that every effort is being expended to deliver a safe, wholesome product to the marketplace. Use of a HACCP system and maintenance of HACCP records show that an industry is making that effort.

When an outbreak of foodborne disease occurs, regulatory efforts usually begin with the distributor and move upstream to the processor and then the supplier (Cliver and Atwill, 1997). When vegetable crops are implicated as the source, the contamination might have occurred anywhere between the field and the table, yet the grower, even if not responsible, is frequently faced with loss of markets or discounted prices. The publicity surrounding an outbreak alone may collapse the market for a vegetable.

While certain elements of the fresh vegetable industry debate the merits of establishing a HACCP system or of using the term *HACCP*, markets may demand HACCP records from suppliers as a condition of purchase. Certain processors and distributors of fresh fruits and vegetables, which includes restaurants and supermarkets, have already been advised to purchase raw materials only from those suppliers that carry safe products (Fain, 1994). For example, the Arkansas-based Harps Food Stores, Inc., began requiring HACPP records from suppliers in 1994 (Waterfield, 1996). The Taco Bell restaurant chain compels its suppliers to follow HACCP plans (NACMCF, 1998). Taco Bell suppliers must keep records on their products as well as of growers supplying the raw material. The demand for verification that fresh vegetables are free of hazards, or nearly so, appears likely to spread throughout the industry as restaurants with salad bars and supermarket chains advertise their participation in food safety programs. Thus, market forces rather than governmental regulations may require each level of the fresh fruit and vegetable industry, from grower to marketer, to adopt at least some form of a food safety system, whether it be called Good Agricultural Practice, Good Manufacturing Practice, or HACCP.

D. Important CCPs in the Production, Sale, and Consumption of Fresh Vegetables

Three critical control points that are especially important in controlling microbial contamination of fresh fruits and vegetables are worker activities, water, and containers and equipment.

1. Workers

People who harvest the vegetable into containers; sort the product for defects, maturity, or size; or prepare the vegetable for consumption can directly contaminate the vegetable with human pathogens and parasites (see Chap. 21). This hazard can be greatly reduced if not prevented entirely by carefully managing worker activities. For example, workers with illnesses or open sores, etc., should not be allowed near the vegetable process flow.

Since certain individuals can appear well and still shed pathogens or parasites, direct skin contact between workers and vegetables should be minimized. Well-stocked facilities for washing hands and sanitizing equipment should be convenient and readily available in the workplace. Verification and monitoring of proper use of these facilities by employees, however, can be very difficult, as with all personal hygiene situations. Nevertheless, businesses can promote cleanliness by providing training; a clean, well-lit, and comfortable workplace; and clean rest rooms. Professional workers who are trained in HACCP procedures are least likely to contaminate vegetables and most likely to recognize when critical limits are being approached.

2. Water

Water is arguably second only to workers as a likely way for hazardous microorganisms to enter a crop. Contaminated water should not be applied to the crop for any reason. This includes water used for irrigation as well as that used for washing or handling. Pesticide sprays are frequently overlooked as a way that microorganisms can be introduced into a crop. Although pesticides are popularly viewed as toxic to all forms of life, the active ingredients do not sterilize the water used to disperse the pesticide into the crop. On the other hand, spray applications deposit very small amounts of water on plant surfaces. Whether a thin film of polluted water on a vegetable surface can establish a harmful contamination is not clear. By contrast, vegetables sprinkle-irrigated with contaminated water are hazardous to consume raw (see Chap. 21).

3. Containers and Equipment

The various inanimate surfaces that contact vegetables during production, harvest, handling, and marketing are a third likely source of undesirable microorganisms. Containers used to haul fruits and vegetables from field to packinghouse have often been cited as a source of postharvest decay pathogens (Brown, 1995). Additionally, certain food-borne outbreaks of human illness have been traced to the contamination of fresh fruits and vegetables by transportation vehicles (Centers for Disease Control and Prevention, 1991). These outbreaks could have been prevented if the equipment had been cleaned and sanitized before use.

E. At-risk Produce

Vegetables that have a history of being a source of foodborne disease outbreaks have generated special handling rules (Golden et al., 1993). Fruits or vegetables that grow in contact with soil and have been involved in more that one outbreak of foodborne illness (such as melons) require special handling precautions. For example, according to FDA regulations, melons must be washed before they are cut, utensils and work surfaces must be cleaned and sanitized, and the cut pieces must be stored at or below 45°F (7°C), and sold or served within 4 h if not refrigerated.

Current news reports about raw apple cider, various fresh fruit and vegetable juices, and seed sprouts (in particular alfalfa sprouts) suggest that additional handling rules might be forthcoming. The rules may require treatment to pasteurize or sterilize juices. If the product is not so treated, warning stickers may be required on containers of the product, such as those now required for unpasteurized apple cider. An alternative in certain cases is to issue a warning to those with impaired immune systems to avoid the product.

III. SANITATION

Sanitation is defined in *The New Lexicon Webster's Dictionary of the English Language* as ''the provision of means whereby health is protected....'' Although sanitation is not directly part of HACCP systems, it is extremely important in the production of wholesome vegetables that have long postharvest lives. Sanitation is important in the field, at the packinghouse, in trucks, at distribution centers, and in the market. A failure to provide proper sanitation at any of these production and marketing steps can create an unacceptable hazard for those downstream in the product flow. Sanitation involves steps taken to eliminate sources of undesirable microorganisms so that vegetables do not become contaminated. Sanitation practices may also be applied directly to vegetables for removal of undesirable microbes.

A. Cleaning Vegetables

The surfaces of freshly harvested vegetables will always contain living populations of bacteria and fungi and will also often have residues of soil, plant material, pesticides, etc. Spray washes are applied at a packinghouse to clean the vegetables. A portion of the microbial population on vegetables is removed by these washes (Goepfert, 1980). However, microbes inside vegetables or in lesions or latent infections are not affected by washes. Moreover, washes cannot remove microbes embedded in active or dried microbial colonies, surface mold growth, etc., until the matrix containing the microbe is removed or dispersed. Microbes not embedded in a matrix are likely to be attached to a surface and/or covered with a protective biological coating (Carlson, 1991). The attachment and the coating tend to protect the microbe from harmful elements in its environment. Ideally, the washing process should be vigorous enough to dislodge the microorganisms, disperse matrices harboring microbes, and remove soil or other matter, but not so strong as to force water into the vegetable (see below) or damage the product. A potable water wash will remove soil and other debris and reduce bacterial numbers by 1 to 2 $\log_{10}$ units (Abdelnoor et al., 1983; Adams et al., 1989; Beuchat, 1992; Brackett, 1992). Houang et al. (1991) showed that agitating a salad in a colander under running tap water for 2 min can reduce the bacteria count by 1 $\log_{10}$ unit. Plant sap from injured tissues, which promotes microbial growth, is also removed by water washes (King and Bolin, 1989).

Regulations for disposal of wash water and the difficulty of obtaining sufficient quantities of potable water for ''once through'' water handling/washing systems have led most packinghouses to recycle water during a workday. Soil, debris, microbes, waxes, and plant sap washed from vegetable surfaces accumulate in the water as it circulates through the system. The water must be treated to control the accumulation of microbes (see below) or each vegetable that enters the system will become contaminated.

B. Removal of Residual Water Left by Washing

Bacteria can multiply in water on vegetable surfaces, particularly if tissue injuries are present and temperatures are high (Goepfert, 1980; Lund, 1992). Free water also promotes spoilage and decay (Bartz and Eckert, 1987). Prompt removal of free water from washed vegetables followed by an immediate cooling are important in the prevention of postharvest decays and may be important in slowing or preventing the development of other microbial hazards. Vegetables are ''dried'' in different ways. A series of sponge rollers in the packing line ''sponge'' free moisture from the surface of tomatoes, potatoes, and certain other vegetables, leaving a semidry product. Because of the equipment design (sponges absorb water from vegetable surfaces and then are squeezed by metal rollers located beneath the sponge bed to remove the water), however, sponge rollers cannot remove all moisture. By remaining wet during the workday as well as between workdays, sponge beds may support the development of biofilms (see Chap. 21), which can contaminate the surfaces of the freshly washed vegetables.

Vegetables that are predisposed to postharvest spoilage by surface wetness may be dried with heated air. Leafy vegetables may be spun dry in centrifugal dryers. High-speed laminar-flow air is also used to break up water films on vegetables. Certain types of cooling, including vacuum cooling and forced-air cooling, remove water from vegetable surfaces. Drying by cooling has the added advantage of reducing the vegetables' temperature, which slows both microbial growth and senescence of the vegetable.

Certain vegetables are handled dry in an effort to reduce water-assisted spoilage and decay. For example, pepper fruit is easily infiltrated with water, a condition that often leads to internal decay. Therefore, peppers may be ''dry dumped'' on padded conveyors and then cleaned by dry brushes or spray washers. In completely dry systems, plant residues and microbial populations can accumulate on machinery surfaces. Dry-dump dry-brush systems have a great potential for becoming heavily contaminated with many different types of microorganisms unless the line is cleaned regularly.

By washing equipment and containers prior to use in the harvest of vegetables as well as routinely during the harvest season, the numbers and types of microorganisms that contaminate vegetable surfaces as a result of harvest are reduced. The firm impact of freshly harvested plant material on container surfaces will often leave deposits of the natural plant waxes and epiphytic microorganisms from the plant surfaces. When wounds on the plant material contact container surfaces, residues of plant sap are left behind, whereas an impact with decayed matter leaves a sticky residue of pathogens and spoiled plant tissues. Soil deposits may contain decay pathogens, such as *Geotrichum candidum* (Brown and Wardowski, 1984). The residues on container surfaces from all forms of contamination provides an ideal matrix for the survival of microorganisms. Washing these residues from container surfaces with detergent and potable water will remove most microorganisms, including plant pathogens, but washing by itself will not reliably decontaminate the surfaces (Goepfert, 1980). Whether the surfaces must be treated with a sanitizer in addition to soap and water depends on the type of contamination that has occurred. For fungal postharvest pathogens, the number left on a freshly washed surface may not be significant in comparison to the total microbial population on the vegetable. Brown (1995) noted that a single spore of *Penicillium digitatum* (cause of green mold) can infect a fresh wound in citrus, but it usually does not. If many spores landed in a fresh wound, however, the wound would usually become infected. The same principle is applicable to vegetables. With proper cooling and handling of a vegetable, contamination by a few postharvest pathogens is unlikely to initiate decay or premature spoilage.

C. Water Chlorination

1. Chemistry

The most common agent used in the fresh vegetable industry to sanitize water systems is hypochlorous acid, usually referred to as chlorine. Hypochlorous acid is produced by the addition of a hypochlorite salt [usually $NaOCl$ or $Ca(OCl)_2$] or chlorine gas (Cl_2) to water. When a salt is used, the ion reacts with a hydrogen ion to yield hypochlorous acid.

When chlorine gas is injected into water, the element instantly hydrolyzes with water: $Cl_2 + H_2O \rightarrow HOCl + H^+ + Cl^-$ (Morris, 1978; White, 1992). The critical value for the chlorination of water used for sanitation in packinghouses or other handling of fresh fruits and vegetables is the free chlorine concentration. Free chlorine is the sum of the concentrations of all species of unreacted oxidative chlorine, which in most solutions are hypochlorous acid (HOCl) and hypochlorite ion (OCl^-) (Bartz and Eckert, 1987; Morris, 1978; White, 1992). By contrast, the total available chlorine is the sum of concentrations of all chlorine species that are capable of oxidizing iodide ion to the element, I_2. Unfortunately, many of the chlorine species that convert iodide ion to iodine are not effective sanitizing agents (Carlson, 1991, White, 1992). Both free and total chlorine concentrations are based on the weight of elemental chlorine that produces the different oxidative species rather than the combined weights of those species. Thus, chlorine concentration in water can be expressed as milligrams of $Cl_2/L\ H_2O$ (ppm) without accounting for each of the chemical forms of oxidative chlorine in solution (Bartz and Eckert, 1987).

Both HOCl and OCl^- are strong oxidizers that react with other dissolved chemicals as well as organic matter, microbes, and even certain relatively inert materials such as metal or wooden surfaces (Brown, 1995). However, hypochlorous acid is 20 to 300 times more lethal to microbes than hypochlorite ion, apparently because the acid penetrates into cells, whereas the charge on the ion prevents it from doing so (White, 1992; Carlson, 1991). At equal free chlorine concentrations, solutions with 99% HOCl kill microbes 250 times more rapidly than those with 99% OCl^- (Pryor, 1950).

2. The Solution pH

The ratio of OCl^- to HOCl in chlorinated water is primarily controlled by the pH of the solution. At pH 7.5, the ratio of acid to ion is approximately 50:50 (White, 1992). At pH 6.0, about 97% of the free chlorine in solution is HOCl, whereas at pH 9.0, 97% of the free chlorine is OCl^-. Small changes in the ratio accompany changes in temperature and concentration of salt (Cl^- and other ions). The concentration of the element, Cl_2, in chlorinated water is extremely small. With a solution of 500 ppm free chlorine at 15°C, Cl_2 concentrations are < 0.001, 0.026, and 0.260 ppm at pH 6.0, 5.0, and 4.0, respectively. These concentrations are much lower than the maximum solubility of chlorine gas in water, which is 5700 ppm at 30°C (Handbook of Chemistry and Physics, 1974). Thus, the chlorinated water systems in packinghouses contain only a trace of chlorine gas. The off gassing or the bubbling of elemental chlorine out of the solution should not occur unless the pH falls to 3.0 or below or chlorine injectors are not working properly (White, 1992). By contrast, the chlorine odor associated with chlorinated packinghouse water systems would either be a product of an autocatalytic breakdown of a hypochlorite solution or of a reaction of hypochlorite with a nitrogenous compound (White, 1992).

3. Chlorine Demand

When organic matter, dissolved chemicals, vegetable surfaces, microorganisms, etc., react with free chlorine in water systems, the active oxidizer disappears (Dychdala, 1991; White, 1992). The matter reacting with chlorine is collectively termed *chlorine demand.* The products of such reactions are nontoxic or relatively nontoxic to microbes. Thus, as the vegetables move through a packinghouse water system, the concentration of free chlorine resulting from a single dose of chlorine to the system will eventually disappear. Products containing free chlorine are added periodically or continuously to the system to replace the lost chlorine. The rate of the free chlorine loss depends on the form of chlorine in the water, the amount and type of demand, and the temperature of the solution. Hypochlorous acid has been estimated to be 10,000 times more reactive with nitrogenous compounds than hypochlorite ion (Morris, 1978). Thus, chlorine solutions containing mostly HOCl would be highly effective against microorganisms but relatively unstable. Chlorine additions would be required more frequently to maintain an effective free chlorine residual. The OCl^- in chlorinated water can be regarded as a potential pool of HOCl (White, 1992). However, the concentration of HOCl must be large enough to kill suspended microbes quickly if the solution is sanitize effectively.

Certain amino acids and ammonium ion react extremely rapidly with HOCl to produce chloramines, which are part of the combined chlorine fraction of chlorinated water (White, 1992). At the high chlorine concentrations used in packinghouse systems, mono-, di-, and trichloramines are likely to be formed. However, most of the monochloramine will be converted to dichloramine. Dichloramine quickly breaks down into various simple nitrogen compounds—such as NH_3, N_2, NO, or NO_3^-—or is converted to trichloramine (White, 1992). Trichloramine is highly unstable in light and insoluble in water. It is the most toxic but least water-soluble of the group, and is easily ''air-stripped'' from water. Trichloramine is the chlorine species responsible for causing tears in workers and has been associated with delignification of the wood in storage facilities (White, 1992). Delignification, which is the destruction of lignin in wood, has also been reported to occur when wooden field bins are disinfected with chlorine solutions or when bins filled with oranges are drenched with chlorinated water (Brown and Wardowski, 1984).

4. Chlorine Products Used for Sanitation

The type of chlorine product used affects how the system is managed. Chlorine gas requires more safety measures than the other chlorine products but is less messy and often less expensive for large-volume use (White, 1992). When chlorine gas is injected into water, the solution becomes acidic owing to the production of hydrochloric acid, as noted above. If the solution becomes too acidic ($pH < 3.0$), the gas either dissolves as the element or bubbles out of the water, both of which are undesirable. Consequently, buffers are needed to remove excess H^+. Most natural water sources contain dissolved bicarbonate ion (HCO_3^-), which reacts with H^+. The initial addition of chlorine gas to such water will not likely produce an undesirable pH. However, as chlorine gas is added to replace the free chlorine lost to demand reactions, buffers such as calcium carbonate, calcium oxide, sodium bicarbonate, or sodium carbonate must be added to remove excess hydrogen ions (White, 1992).

The initial mixing of chlorine gas with water at injectors may temporarily produce undesirably low pH levels (White, 1992). By design, commercial chlorine injectors limit gas additions to a maximum of 3500 ppm at the injector outlet, but the operation is contingent on a proper mixing of chlorine gas with water. Even with ample buffer concentrations and the best system for mixing chlorine with water, solution pH levels at the injector outlet fall below 4.0 and a significant portion of the gas dissolves in the water as the element. Therefore, water movement by chlorine injectors must readily disperse the incoming gas but not be so turbulent as to airstrip elemental chlorine from the water.

When solutions of hypochlorite ion are used to maintain free chlorine concentrations in packinghouse systems, the solution pH tends to increase. Concentrated bleach solutions (5.25% to 15% sodium hypochlorite) are manufactured by bubbling chlorine gas through a solution of sodium hydroxide (White, 1992). The autocatalytic loss of free chlorine from liquid bleach is slow at pH levels above 11.0. Consequently, excess hydroxide ion and/

or sodium carbonate are present in finished bleach as stabilizers. Thus, as liquid bleach is added to water systems to maintain free chlorine concentrations, the pH of the water increases owing to an accumulation of OH^-, HCO_3^-, or CO_3^{2-}. Certain reactions of hypochlorous acid in water systems also produce hydroxyl ions. For example, as HOCl disappears, OCl^- removes H^+ from the solution to reestablish the equilibrium determined by pH. By contrast, the oxidation of H_2S and certain other demand reactions produce acids. The balance, however, favors the production of hydroxyl ions. Thus, recycled water systems chlorinated with liquid bleach must be treated with acidic buffering substances to maintain desired pH levels.

Dry chlorine products, such as calcium hypochlorite, release hypochlorite into water as the powder or granule dissolves (White, 1992). Dry products are stable, relatively compact, and easy to handle but can be difficult to meter into water. This product must be stored away from reducing agents or high temperatures, since containers of calcium hypochlorite can ignite if heated. The addition of calcium hypochlorite to water usually produces residual cloudiness due to the production of insoluble calcium compounds. When used in recycled water systems, this form of hypochlorite increases the pH of the water although usually not as rapidly as liquid bleach.

5. Chlorine Concentration and pH Level Required for Sanitation

The chlorine concentration and pH level needed to sanitize a recycled water system in a packinghouse must be based on operating conditions. Carlson (1991) argued that chlorine treatment parameters for potable water had to be based on facility performance and not extrapolation from laboratory tests. Fluctuation in chlorine demand, including types and numbers of contaminants as well as the microbial structures entering the system, influence how the water must be treated.

Chlorine is used in different ways in the postharvest environment. Each type of use affects how rapidly chlorine must kill microbes. The rate-of-kill requirement dictates chlorine concentrations, solution temperatures, and solution pH. When used to clean equipment, chlorinated water can be left on equipment surfaces. This allows a longer contact interval and less free chlorine is required. When used to treat water that contacts the product, chlorine must prevent transfers of micro-organisms from the water to the vegetable or among vegetables in the water. This requirement calls for rapid activity, since once certain types of contamination occur, the product cannot be reliably decontaminated (Fain, 1994). Rapid activity requires higher chlorine concentrations, a pH assuring mostly hypochlorous acid in the water, and higher solution temperatures. Robbs et al. (1995) reported that 0.5 to 1.0 ppm of free chlorine at 24°C and a pH of 6.0 to 8.0 killed washed cells of *Erwinia carotovora* subsp. *carotovora* (the cause of bacterial soft rot) within seconds. By contrast, spores of *G. candidum* survived exposure for 2 min to concentrations up to 20 ppm at pH 6.0 or 7.0 and more than 30 ppm at pH 8.0. Brown and Wardowski (1984) observed that 100 ppm free chlorine at pH 7.0 killed washed and then suspended spores of *G. candidum* within 10 s; but with a 15-s exposure, 1000 ppm killed only 57% of the naturally occurring spores of this pathogen on unwashed oranges. Bender et al. (1992) reported that the chlorination of water (pH 7.0 and 38°C) in a flume and washer in a commercial packinghouse to 50 ppm provided as much control of postharvest decays for tomatoes as did 80 or 100 ppm. In two separate tests, tomatoes from all treatments had less than the 5% decay allowed by grade standards after a 2-week storage interval. Thus, the 100 to 150 ppm recommended for tomato packinghouses in Florida (Hicks and Segall,

1974) included an overdose that was apparently intended to maintain acceptable free chlorine concentrations between periodic additions of chlorine product to the system.

Free chlorine kills microbes more rapidly as water temperature increases. Cysts of the intestinal parasite *Giardia lamblia* are considered among the more resistant microbes of concern in treatment plants for potable water (Clark et al., 1989). The ED_{99} of free chlorine for a 1-min exposure ranged from 14.5 to 526 ppm, depending on water temperature (0.5 to 25°C) and pH (6.0 to 8.0). The largest dose was required in the coolest water and at the highest pH. Ferriera (1994) found that the minimum concentration of free chlorine required to kill spores of *Rhizopus stolonifer* within 2 min at pH 7.0 was 40, 80, and 120 ppm, at 40, 24, and 5°C, respectively.

6. Maintaining Adequate Free Chlorine Concentrations in Water Systems

Various methods have been used to maintain the desired free chlorine concentration in recycled water systems. The most reliable are automated and demand-driven. One such system uses platinum electrodes to measure the oxidation-reduction potential (ORP) in the water, which is highly correlated with the antimicrobial activity in the water (Carlson, 1991; Robbs et al., 1995). A computer uses output from the platinum electrodes as well as pH probes to start pumps that inject chlorine and buffer as needed to maintain a desired oxidation-reduction potential. Problems with this system include the facts that platinum electrodes are not highly sensitive to small shifts in ORP at the chlorine concentrations used in vegetable packinghouses, the electrode output may be affected by the water's poise (or the oxidation-reduction potential of the water prior to chlorination), and electrodes can become ''poisoned'' by exposure to high chlorine concentrations (White, 1992). However, the system automatically maintains the oxidation-reduction potential in a desirable range. A second automated system utilizes N,N-diethyl-p-phenylenediamine (DPD) tests taken every 2.5 min (Hach Inc., Chlorine Analyzer, Model CL17). An alarm sounds if the free chlorine concentration is outside of set points. The operators are responsible for changing the rate of chlorine addition or adjusting pH.

D. Alternatives to Chlorine/Hypochlorite for Sanitation

Alternatives to chlorine are being sought because of the tendency of water chlorination to produce halomethanes if the water contains certain organic matter (White, 1992). Halomethanes are perceived to be hazardous.

1. Ozone

Ozone, the most powerful oxidant that can be safely used to treat water (Waite, et al., 1978), kills a wide variety of microorganisms quickly. The shelf life of oranges, strawberries, raspberries, grapes, apples, and pears was reportedly extended by ozone treatment of the wash water (Beuchat, 1996; Horvath et al., 1985). The chemistry of ozone in vegetable dump tanks is not clear, although potentially hazardous chlorinated by-products should not be produced. Broadwater et al. (1973) suggested that ozonated water produces an ''all-or-none'' effect on microbes. If sufficient ozone is present, all cells die, whereas insufficient levels have no effect. Washed vegetative cells of three different bacteria had minimum lethal thresholds of 0.12 to 0.19 ppm, whereas unwashed cells survived up to 0.71 ppm. Bacterial spores had a lethal threshold of 2.29 ppm. The authors suggested that, in production of potable water, the raw water might require a dosage of 0.5 to 10.0 ppm for a period of 2 to 10 min. Spotts and Cervantes (1992) did not observe an all-or-none effect in treating spores of three different fungal pathogens of pear fruit. At initial ozone concentrations of 0.2 to 0.3 ppm applied for 1 min, spores of *Botrytis cinerea*, *Mucor piriformis*, and *Penicillium expansum* began to be inhibited. Increasing numbers were inhibited as the concentration increased to approximately 1.5 to 3.0 ppm, where all spores were killed. In a packinghouse water system, ozone functions as a dissolved gas (White, 1992). Consequently, turbulence associated with the unloading of vegetables into the water or the washing of vegetables with water would airstrip ozone from the solution. Spotts and Cervantes (1992) cited difficulty in maintaining adequate residuals for sanitation of the water in dump tanks for pears. Whether this instability was due to ozone's high reactivity with organic matter or to the fact that it was a gas dissolved in water was not clear.

2. Chlorine Dioxide

Chlorine dioxide is being considered as potential sanitizer for water systems and is used in vegetable canning factories to clean recycled water (White, 1992). Chlorine dioxide does not react with amines and amino groups like chlorine and would not produce halomethanes from reaction with organic matter. However, chlorine dioxide dissolves in water as a gas (White, 1992). Consequently, turbulence associated with the dumping of vegetables into water or the spray washing of vegetables is likely to airstrip chlorine dioxide from the system. At equilibrium, a chlorine dioxide concentration of 1 ppm in water would produce 10 ppm of chlorine dioxide in air over the solution; this concentration has an objectionable odor (White, 1992). Roberts and Reymond (1994) reported that 6 ppm in the water system of an apple packinghouse caused "respiratory discomfort" for some workers. They further noted that 3 to 5 ppm would provide an effective residual for controlling fungal spores in apple dump tanks. However, even with 3 ppm, special ventilation equipment would be required if the dump tank system were enclosed with the packing line. Brown and Wardowski (1984) observed that greater than 5 to 10 ppm would be required to inactivate all spores in a citrus soak tank. Spotts and Peters (1980) concluded that an estimated 10 ppm required to obtain significant fungicidal activity in pear packinghouses would be too costly.

E. Hydrogen Peroxide

Hydrogen peroxide is another oxidizing chemical that has been considered as an alternative to chlorine. Although hydrogen peroxide has a higher oxidation-reduction potential than chlorine, it is much less toxic to microbes than chlorine, ozone, or chlorine dioxide (White, 1992). Therefore the usefulness of hydrogen peroxide for sanitizing packinghouse systems is not clear.

F. Problems in Water Chlorination

1. Biofilm Formation

Microorganisms embedded in biofilms can be particularly difficult to destroy. These deposits feature polysaccharides and lipopolysaccharides produced by certain bacteria that enclose the producing bacteria as well as other microorganisms (Carlson, 1991; Waite, et al., 1978). Biofilms form on surfaces that remain wet for prolonged periods of time (Waite, et al., 1978). The film is literally glued to the surface upon which it forms. Free chlorine reacts with the surface of the biofilm but not with the microbes embedded in the film. As noted above, the sponge rollers on certain packing lines are ideal for biofilm development. Unless free available chlorine or another biocide is present in the water removed from the vegetable by the sponge rollers, the rollers are likely to become coated with a biofilm. Anecdotal reports from packinghouse managers that the sponges can become slimy after being used for several days are consistent with the development of heavy biofilms. Whether residual sanitizer removed from vegetables passing over a sponge bed will keep biofilms from forming is not clear.

2. Heavily Soiled Water

Tank water used to handle and wash root crops becomes heavily contaminated with soil and sometimes partially decayed plant debris. Free-chlorine residuals are difficult to maintain in such water owing to the high chlorine demand. However, unless a sanitizing chemical is added to the water, microbes will accumulate. As the inoculum concentration increases, so too will the probability of postharvest decays in the washed vegetable (Bartz and Kelman, 1984). The addition of chlorine to heavily soiled water may help to prevent accumulations of microorganisms even though a free chlorine residual cannot be maintained. For example, a patent was issued for a combination of citric acid, citrate buffer, and hypochlorite that killed bacterial spores contaminating clothing and electronic equipment (Echols et al., 1973). The ingredients were mixed just before use. The solution was 99.9% effective, but all free chlorine was lost within 10 min. Therefore the bleach did not harm the clothing and equipment. Park et al. (1991) describe application of a hypochlorite-and-citrate combination to various types of meat and certain vegetables that had been contaminated with *Salmonella enteritidis*. The sanitizing solution reduced counts up to 4 $\log_{10}$ units within a 20 to 30 min exposure. All free chlorine within the solution disappeared (reacted with the citrate) by about 20 min. In tests with spores of *G. candidum* suspended in diluted tomato juice (pH 7.0), we obtained reduction of at least 3 $\log_{10}$ with a free chlorine concentration that completely disappeared within the 2-min exposure period (Bartz, unpublished). Thus, free chlorine as HOCl reacts extremely rapidly with suspended microorganisms, apparently more rapidly than with many types of chlorine demand.

3. Water Uptake by Vegetables During Handling/Washing Processes

The infiltration of vegetables with water during handling or washing procedures can confound adequate sanitation measures. Although the waxy surfaces of vegetables prevent a direct absorption of water, the water may be forced into natural openings or wounds on the vegetable surface due to various physical forces (Bartz and Showalter, 1981; Bartz, 1982; Bartz and Kelman, 1985). Tomato fruit infiltrated by water contaminated with postharvest pathogens rapidly developed decays (Bartz and Showalter, 1981; Bartz, 1982). The lesions usually began beneath and beside the stem scar. Bacterial cells as well as fungal spores were internalized by infiltration of the vegetable. Chlorination of the water immediately prior to the infiltration of tomatoes failed to prevent decay development (Bartz, 1988). The movement of microbes into plant tissues during infiltration is not limited to postharvest pathogens. Cells of *Salmonella montevideo* infiltrated into tomatoes survived inside the fruit (Zhuang et al., 1995).

Major factors that cause vegetables to be infiltrated with water include the cooling of submerged tissues and hydrostatic forces on tissue surfaces (Bartz and Showalter, 1981; Bartz, 1982). When vegetables cool, the gases in intercellular spaces exert less pressure as predicted by the ideal gas law. If the equilibration of internal gas pressures with air pressure outside the vegetable is blocked by water flooding pores in the vegetables' surface, then a vacuum develops. As the vacuum increases, atmospheric pressures force water into the tissues despite the hydrophobic nature of the surface of the vegetable (Bartz and Showalter, 1981). Warming the water to temperatures similar to or above those of the incoming vegetable can prevent infiltration caused by cooling. Limiting the contact of the vegetable with water such that little cooling occurs also will prevent infiltration.

Purely hydrostatic forces, either accompanying submergence or from a directed stream of water, may also cause the vegetable to become infiltrated with water. As with cooling-induced infiltration, the longer the vegetable is in contact with the water, the more likely water pressure on the vegetable surface will cause infiltration. Therefore, the use of ''soak tanks,'' where vegetables are held under water for several minutes to loosen surface soil, should be reexamined to determine what effect the practice has on the microbial community associated with the finished product. A second, relatively recent innovation, the use of high-pressure spray washers such as used in citrus packinghouses, also should be examined for possible infiltration.

Since surface waxes restrict the movement of water into vegetables, a reduction in the surface tension of the water will reduce the pressure imbalance required to initiate infiltration (Bartz, 1981). Consequently, the addition of surfactants to wash or handling water to achieve better cleansing or wetting of vegetable surfaces must be evaluated carefully.

The correlation between cooling and infiltration and infiltration and decay would appear to rule out submergence hydrocooling as a postharvest practice. However, Ferreira et al. (1996) reported that strawberries could be hydrocooled in water contaminated with spores of *R. stolonifer* or *B. cinerea* if the water also contained 120 mg/L of chlorine at pH 6.0. In the absence of the chlorine, the berries developed nearly 100% decay.

IV. SANITATION BEYOND THE PACKINGHOUSE

Use of sanitation in the preparation of vegetables in the home or restaurant kitchen may be more important in avoiding food-borne diseases than use of HACCP and sanitation by the fresh vegetable industry (Fain, 1994). Vegetables intended for raw consumption should never contact fresh animal products or surfaces (including knives, hands, etc.) that have been in contact with fresh meat products. The resulting cross-contamination has been frequently cited as responsible for disease outbreaks (see Chap. 21).

The surfaces of fresh fruits and vegetables must be clean before the product is cut. For example, in the preparation of watermelon slices, use of a contaminated knife or cutting through contaminated fruit surfaces is likely to contaminate the flesh of the slices with pathogens such as *Salmonella* spp. (Gayler et al., 1955; CDC, 1979). With tomatoes, Lin and Wei (1997) showed that cutting through stem scar tissues containing *S. montevideo* at populations less than 10 CFU transferred the bacteria to the interior flesh of the fruit. When the bacterial population at the stem scar was increased, *S. montevideo* could be transferred to another noninoculated tomato by the contaminated knife.

REFERENCES

Abdelnoor, A. M., Batshoun, R., and Roumani, B. M. 1983. The bacterial flora of fruits and vegetables in Lebanon and the effect of washing on the bacterial content. Zbl. Bakt. Hyg. I. Abt. Orig. B. 177:342–349.

Adams, M. R., Hartley, A. D., and Cox, L. J. 1989. Factors affecting the efficacy of washing procedures used in the production of prepared salads. Food Microbiol. 6:69–77.

Bartz, J. A. 1981. Ingress of suspensions of *Erwinia carotovora* subsp. *carotovora* into tomato fruit. p. 452–460. In: J. C. Lozano, ed. Proceedings of the 5th International Conference on Plant Pathogenic Bacteria. Centro Internacional de Agriculturia Tropical. Cali, Colombia.

Bartz, J. A. 1982. Infiltration of tomatoes immersed at different temperatures to different depths in suspensions of *Erwinia carotovora* subsp. *carotovora*. Plant Dis. 66:302–306.

Bartz, J. A. 1988. Potential for postharvest disease in tomato fruit infiltrated with chlorinated water. Plant Dis. 72:9–13.

Bartz, J. A., and Kelman, A. 1984. Inoculation of potato tubers with *Erwinia carotovora* during simulated commercial washing and fluming practices. Amer. Potato J. 61:495–507.

Bartz, J. A., and A. Kelman. 1985. Infiltration of lenticels of potato tubers by *Erwinia carotovora* pv. *carotovora* under hydrostatic pressure in relation to bacterial soft rot. Plant Dis. 69:69–74.

Bartz, J. A., and Showalter, R. K. 1981. Infiltration of tomatoes by bacteria in aqueous suspension. Phytopathology 71:515–518.

Bartz, J. A., and Eckert, J. W. 1987. Bacterial diseases of vegetable crops after harvest, p. 351–375. In: J. Weichmann (ed.). Postharvest physiology of vegetables. Marcel Dekker, New York and Basel.

Bender, R. J., Sargent, S. A., Brecht, J. K., and Bartz, J. A. 1992. Effect of tomato grade on incidence of decay during simulated shipping. Proc. Fla. State Hort. Soc. 105:119–121.

Beuchat, L. R. 1992. Surface disinfection of raw produce. Dairy Food Environ. Sanit. 12:6–9.

Brackett, R. E. 1992. Shelf stability and safety of fresh produce as influenced by sanitation and disinfection. J. Food Prot. 55:808–814.

Broadwater, W. T., Hoehn, R. C., and King, P. H. 1973. Sensitivity of three selected bacterial species to ozone. Appl. Microbiol. 26:391–393.

Brown, G. E. 1995. Sanitation in the packinghouse for citrus decay control, p. 2–4. In: W. Wardowski (ed.). Packinghouse Newsletter No. 174. University of Florida Institute of Food and Agricultural Sciences, Cooperative Extension Service, Gainesville.

Brown, G. E., and Wardowski, W. F. 1984. Use of chlorine and chlorine dioxide in Florida citrus packinghouses to reduce inoculum of decay pathogens. Proc. Fla. State Hort. Soc. 97:97–100.

Carlson, S. 1991. Fundamentals of water disinfection. J. Water SRT—Aqua 40:346–356.

Centers for Disease Control and Prevention (CDC). 1979. *Salmonella oraninebury* gastroenteritis associated with consumption of precut watermelons-Illinois. M.M.W.R. 28:522–523.

Clark, R. M., Read, E. J., and Hoff, J. C. 1989. Analysis of inactivation of *Giardia lamblia* by chlorine. J. Environ. Eng. 115:80–90.

Cliver, D. O., and Atwill, E. R. 1997. Research and reason can minimize foodborne and waterborne illnesses. Calif. Agr. 51:8–14.

Echols, W. H., Fielding, G. H., and Neihof, R. A. 1973. Method of disinfecting and self-limiting solution therefor. United States Patent Office. No. 3,717,580. Feb. 20, 1973.

Dychdala, G. R. 1991. Chlorine and chlorine compounds, p. 131–151. In: S.S. Block (ed.). Disinfection, sterilization, and preservation. 4th ed. Lea & Febriger, Philadelphia.

Fain, A. R. 1994. A review of the microbiological safety of fresh salads. SCOPE: A Technical Bulletin from Silliker Laboratories. September issue, p. 1–4.

Ferriera, M. D. 1994. Physiological responses of strawberry to handling impacts and precooling methods. M.S. thesis. University of Florida.

Ferriera, M. D., Bartz, J. A., Sargent, S. A., and Brecht, J. K. 1996. An assessment of the decay hazard associated with hydrocooling strawberries. Plant Dis. 80:1117–1122.

Gayler, G. E., MacCready, R. A., Reardon, J. P., and McKernan, B. F. 1955. An outbreak of salmonellosis traced to watermelon. Public Health Rep. 70:311–313.

Goepfert, J. M. 1980. Vegetables, fruits, nuts, and their products, p. 606–642. In: J. H. Silliker, R. P. Elliot, A. C. Baird-Parker, F. L. Bryan, J. H. B. Christian, D. S. Clark, J. C. Olson, Jr., and

T. A. Roberts (eds.). Microbial ecology of foods. Vol. II. Food commodities. International Commission on Microbiolgical Specifications for Foods. Academic Press, NY.

Golden, D. A., and Rhodehamel, E. J., and Kautter, D. A. 1993. Growth of *Salmonella* spp. in cantaloupe, watermelon and honeydew melons. J. Food Prot. 56:194–196.

Gottwald, T. R., Graham, J. H., and Schubert, T. S. 1997. Citrus canker in Urban Miami: An analysis of spread and prognosis for the future. Citrus Industry: August 5.

Houang, E., Bodnaruk, P., and Ahmet, Z. 1991. Hospital green salads and the effects of washing them. J. Hosp. Infect. 17:125–131.

Horvath, M., Bilitzky, L., and Huttner, J. 1985. Ozone. Elsevier, Amsterdam.

Hicks, J. R., and Segall, R. H. 1974. Water chlorination for vegetable packinghouses. Vegetable Crops Fact Sheet VC-1, Florida Cooperative Extension Service, University of Florida, Institute of Food and Agricultural Sciences, Gainesville, FL.

Janisiewicz, W. J., Conway, W. S., Brown, M. W., Sapers, G. M., Fratamico, P., and Buchanan, R. L. 1998. Growth and insect transmission of *Escherichia coli* on wounded apples (abstr). Phytopathology 88:S43.

King, A. D., and Bolin, H. R. 1989. Physiological and microbiological storage stability of minimally processed fruits and vegetables. Food Technol. 43(2):132–136.

Lin, C.-M., and Wei, C. I. 1997. Transfer of *Salmonella montevideo* onto the interior surfaces of tomato by cutting. J. Food Prot. 60:858–863.

Lund, B. M. 1992. Ecosystems in vegetable foods. J. Appl. Bacteriol. Suppl. 73:115S–126S.

Morris, J. C. 1978. The chemistry of aqueous chlorine in relation to water chlorination, p. 27–35. In: R. L. Jolley (ed.). Water chlorination: Environmental impact and health effects. Vol. 1. Ann Arbor Science, Ann Arbor, MI.

U.S. Food and Drug Administration, National Advisory Committee on Microbiological Criteria for Foods (NACMCF). 1998. Microbiological Safety Evaluations and Recommendations on Fresh Produce. U.S. FDA, Washington, DC.

Park, D. L., Rua, S. M., Jr., and Acker, R. F. 1991. Direct application of a new hypochlorite sanitizer for reducing bacterial contamination on foods. J. Food Prot. 54:960–965.

Pryor, D. F. 1950. Reduction of post-harvest spoilage in fresh fruits and vegetables destined for long distance shipment. Food Technol. 4:57–62.

Robbs, P. G., Bartz, J. A., Brecht, J. K., and Sargent, S. A. 1995. Oxidation-reduction potential of chlorine solutions and their toxicity to *Erwinia carotovora* subsp. *carotovora* and *Geotrichum candidum*. Plant Dis. 79:158–162.

Roberts, R. G., and Reymond, S. T. 1994. Chlorine dioxide for reduction of postharvest pathogen inoculum during handling of tree fruits. Appl. Environ. Microbiol. 60:2864–2868.

Spotts, R. A., and Peters, B. B. 1980. Chlorine and chlorine dioxide for control of d'Anjou pear decay. Plant Dis. 64:1095–1097.

Spotts, R. A., and Cervantes, L. A. 1992. Effect of ozonated water on postharvest pathogens of pear in laboratory and packinghouse tests. Plant Dis. 76:256–259.

Waite, T. D., Jorden, R. M., and Kawaratani, R. 1978. Evaluation of alternative chemical treatments for biofouling control in electric power facilities, p. 753–771. In: R. L. Jolley (ed.). Water chlorination: Environmental impact and health effects. Vol. 1. Ann Arbor Science, Ann Arbor, MI.

Waterfield, L. 1996. FMI focuses on microbes. The Packer, Dec. 9, 1996.

Weast, R. C. (ed.). Handbook of Chemistry and Physics, 55th ed. 1974–1975. CRC Press., Cleveland, OH.

White, G. C. 1992. Handbook of chlorination and alternative disinfectants. 3rd ed. Van Nostrand Reinhold, New York.

Zhuang, R. Y., Beuchat, L. R., and Angulo, F. J. 1995. Fate of *Salmonella montevideo* on and in raw tomatoes as affected by temperature and treatment with chlorine. Appl. Environ. Microbiol. 61:2127–2131.