Food Engineering Series
Series Editor: Gustavo V. Barbosa-Cánovas

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Advances in Food Process Engineering Research and Applications

Springer

Chapter 18
Nonthermal Technologies to Extend the Shelf Life of Fresh-Cut Fruits and Vegetables

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18.1 Introduction

Natural, healthy, and functional foods are becoming major features for markets in Europe and other developed countries. Consumers are increasingly seeking products that retain natural nutrition, flavor, texture, and color properties. The fresh-cut fruit and vegetable market has grown rapidly in recent decades. In 2003 the fresh-cut industry represented 50 % of fresh produce sales (Zaborowski 2003), and in 2007 retail sales accounted for $998.25 billion (Cook 2007) in the USA. Meanwhile, in Germany the turnover of fresh food industries was around €52 billion in 2000 (Entrup 2005), with justifiable expectations of continued increase due to the popularity of fresh food as a convenient and healthy food choice (Artés and Allende 2005; Rico et al. 2007).

The International Fresh-Cut Produce Association (IFPA) defines fresh-cut products as fruits or vegetables that have been trimmed or peeled, or cut, into a 100 % usable product that is bagged or prepackaged to offer consumers high nutrition, convenience, and flavor, while still maintaining freshness. The value of fresh-cut produce lies in the primary characteristics of freshness and convenience. Achieving food safety and retaining nutrition and sensory quality are also required, while providing extended shelf life (González-Aguilar et al. 2004).

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S. Yanniotis et al. (eds.), *Advances in Food Process Engineering Research and Applications*, Food Engineering Series, DOI 10.1007/978-1-4614-7906-2_18,

Interestingly, one of the most challenging problems in the commercialization these products is usually their short shelf life and declining quality after processi (Du et al. 2009; Jacxsens et al. 1999). The shelf life of fresh-cut fruits a vegetables varies from 3 to 7 days and depends on the product; however, a lon shelf life is better to make safe distribution feasible. Shelf life is the time a prod can retain its quality under standardized storage conditions before its attributes dr below the acceptance limit (Tijskens 2000). It is broadly believed that processing of fruits and vegetables promotes faster physiological deteriorati biochemical changes, and microbial degradation of the product, even when mi mal processing operations are applied (O'Beirne and Francis 2003). These chang such as degradation of color, texture, and flavor, will reduce the shelf life of th products compared to unprocessed products (Watada et al. 1990).

Furthermore, providing information about the safety of these products is still issue of heightened concern to consumers. Meanwhile, fresh-cut fruits a vegetables are highly perishable since a large proportion of those damaged h exposed surface areas without epidermis, i.e., the outer protective layer of the tis (Sandhya 2010; Watada and Qi 1999). Therefore, the fresh-cut produce industr challenged with potential outbreaks of illness that could be associated with mic bial growth during the extended shelf life of these products (Alzamora and Guerr 2003). This threat is due to the fact that these products provide a viable medium the growth of microorganisms.

In response to these challenges, many efforts using recent science technologies have been devoted to prolonging the shelf life of these products to improving their quality and safety. Extended shelf life of foods has tradition been linked with thermal processing. Heat treatment, however, leads to the destr tion of freshness and to nutrient losses. As a consequence, it is imperative that n preservation methods be found that cause only minimal adverse changes in foo with limited (or no) use of additives, while offering desirable benefits derived fr an increased shelf life (Camelo et al. 2003). One approach that promises to incre the shelf life of fresh-cut products is to use nonthermal technologies, which, some extent, achieve a freshlike quality and safe product and retain high nutritio value. The emergence of novel nonthermal technologies, which are often regar as *invisible preservation*, allows the production of high-quality products w improvements in shelf life and freshlike characteristics. The present revi summarizes recent contributions reported on minimal processing of plant f products using nonthermal technologies to maintain freshness and achieve lon shelf life.

18.2 Physiological Effects of Processing Operations on Fresh-Cut Plant Products

Fresh-cut fruits and vegetables are products partially prepared so that no additi preparation is necessary for their use. Fresh-cut products have also been referre as *lightly processed*, *minimally processed*, *fresh processed*, *partially processed* *reprepared* products (Garcia and Barrett 2005). Generally, it is unavoidable that e overall quality is impaired during processing and storage. The increasing emand for convenient fresh-cut products has a detrimental effect on product uality. Physiologically, the operations of preparation damage the integrity of ells, promoting contact between enzymes and substrates, the entry of icroorganisms, and creation of stress conditions (Fonseca et al. 1999). The onsequences of wounding are (1) an increase in the respiration rate, (2) the roduction of ethylene, (3) oxidative browning, (4) water loss, and (5) degradation f membrane lipids (Brecht 1995, cited in Fonseca et al. 1999). Therefore, fresh-cut uits and vegetables tend to be more perishable than the commodity from which ey were prepared (Kader 2002).

Cutting is the main factor responsible for the deterioration of these products uring storage, which, as a consequence, is more rapid than in unprocessed (whole) roducts (Degl'Innocenti et al. 2007). Damaged plant tissues exhibit an increased spiratory rate (Fonseca et al. 2002). Treatment applied after, or before, wounding an affect the respiration rate (Del Nobile et al. 2006). Therefore, cutting induces eteriorative changes associated with plant tissue senescence and a consequential ecrease in shelf life relative to unprocessed produce.

It is also well established that a faster rate of enzymatic browning by cutting is onsidered to be one of the major limitation factors detrimental to many fresh-cut roducts, such as apples, bananas, potatoes, and lotus root, since browning is easily etected by consumers, with evident consequences for marketing (Degl'Innocenti al. 2007; Luo and Barbosa-Cánovas 1996). Polyphenoloxidase (PPO, C1.14.18.1) activity is known to be the main cause involved in browning (Walker d Ferrar 1998).

Another important enzyme influenced by cutting is lipoxidase, which catalyzes e peroxidation reaction, thereby causing the formation of numerous bad smelling dehydes and ketones (Varoquaux and Wiley 1994). Furthermore, a faster rate of ftening of tissue results from an increase in ethylene production during this fresh- t processing due to the fact that ethylene contributes to the biosynthesis of zymes in fruit maturation and is partially responsible for the physiological anges in sliced fruit.

These physiological changes may be accompanied by flavor loss, cut-surface iscoloration, color loss, decay, increased rate of vitamin loss, rapid softening, rinkage, and a shorter storage life. Increased water activity and mixing of tracellular and intercellular enzymes and substrates may also contribute to flavor d texture change/loss during and after processing (Sandhya 2010). By under- anding the physiology-changing mechanisms of fresh-cut-product processing and ntrolling factors that have a detrimental effect on quality, good-quality fresh-cut oducts with sufficient shelf life can be obtained.

18.3 Nonthermal Technologies

The term *nonthermal processing* is often used to designate technologies that are effective at ambient or sublethal temperatures (Pereira and Vicente 2009) or when the main stress factor for microbial inactivation is not heat. An increase in consumer demand for fresher foods, which at the same time provide a high degree of safety, has driven the growing interest in nonthermal preservation techniques because of their capability to inactivate microorganisms and enzymes in foods (Mertens and Knorr 1992). High capital investment in nonthermal technologies is one of the main issues for commercial application; fortunately, it is usually believed that consumers are willing to pay more when better quality and added value are offered.

Fresh-cut fruits and vegetables have been found to be more prone to pathogen contamination (Farkas et al. 1999). Therefore, nonthermal technologies may play an important role in producing more convenient freshlike products and safe foods as an alternative technology to thermal processing. This review concentrates on physical treatment alternatives to thermal processing. In the following sections, the main emphasis will be on processes already being applied commercially or that are likely to become so in the foreseeable future.

18.4 High-Pressure Processing

Many studies have been conducted to evaluate the safety of high pressure food processing (Zook et al. 1999). It has been suggested that the major cause of damage in microbial inactivation subjected to high pressure is modification of the molecules in cell membranes, leading to permeability (Hoover 1993). Changes in cell morphology involve collapse of intercellular gas vacuoles, cell elongation, and cessation of microorganisms' movement; thus, high-pressure processing (HPP) damages microbial cell membranes (Barbosa-Cánovas and Rodriguez 2002). HPP is based on the principle of *Le Chatelier-Braun* and the state transition theory (Welti-Chanes et al. 2005). The following equations illustrate the work of HPP:

$$\Delta G = G^{(\text{products})} - G^{(\text{reactants})}, \qquad (18.1)$$

where ΔG is free energy, and when ΔG is negative, the reaction is spontaneous.

$$dG = -SdT + VdP + \sum \mu_i dn_i, \qquad (18.2)$$

where S is entropy, V is volume, P is pressure, T is temperature, μ is chemical potential, and n is the number of moles of a compound (Welti-Chanes et al. 2005). The preceding equation is the basic principal equation of Gibbs, while the next equation correlates the influence of pressure on G with volume:

$$V = \left[\frac{\partial G}{\partial P}\right]_{\mathrm{T,ni}}. \qquad (18.3)$$

The increase in pressure leads to damage to the microbial cell membranes, which eventually causes the microbial cell to become inactive; however, this transition condition could avoid the destruction of the covalent bonds that retain natural flavor, taste, color, and nutrients (Hayashi 1995). Thus, the physical structure of most fresh-cut fruit and vegetable products remains unchanged after exposure to HPP.

It has been reported that some problems may arise associated with the use of HPP on certain plant material systems because HPP affects the integrity of porous products. The air confined in the food matrix is subjected to compression and expansion during pressurization and decompression, disrupting food plant tissues, thereby making this unit operation not entirely suitable for all plant products (Palou et al. 2000).

On the other hand, Torres and Velazquez (2005) showed that fresh-cut products represented one of many opportunities in which HPP has a clear competitive advantage. Nishin Oil Mills, a Japanese food manufacturer, has produced nontropical fruits using HPP at pressures of 50–200 MPa ("freezing" temperature, −18 °C) [Campden New Technology Bulletin No. 14; cited in Ohlsson and Bengtsson (2002)]. In addition, Ting and Marshall (2002) illustrated that HPP treatment of fresh-cut fruit produces a very high-quality product with extended shelf life that can also be produced without heating or chemical additives. Palou et al. (2002) added that HPP treatments could preserve the delicate sensory attributes of avocados, which are used in the preparation of guacamole, one of the first HPP-treated food plant products to be commercialized in the USA, demonstrating a reasonably safe and stable shelf life. Several companies (Avure: http://www.nchyperbaric.com and NC Hyperbaric: http://www.avure.com) that manufacture HPP equipment offer promising safety and extended shelf life for fresh-cut fruits and vegetables, such that these products will become more profitable.

The application of HPP on fresh-cut products can be seen in Table 18.1.

In terms of microbial inactivation using HPP treatment on fresh-cut plant products, Alemán et al. (1994) reported application of HPP on fresh-cut pineapple in combination at a pressure of only 270 MPa for 15 min, resulting in more than two decimal reductions at a temperature of 38 °C. Meanwhile, Alemán et al. (1998) reported that step pulsed pressure could reduce the amount of yeast and bacteria at a pressure of 270 MPa for a shorter time, 100 s, as compared to static pressure of 270 MPa for 15 min. Zong and Zhang (2009) emphasized that HPP treatment could effectively kill microorganisms and had a slight influence on the firmness of the product. Moreover, a few years ago, Ramaswamy et al. (2005) stated that spore inactivation was a primary challenge in HPP application; today, the challenge has been answered. Bermudez-Aguirre and Barbosa-Cánovas (2011) emphasized that by utilizing a smart combination of pressure, temperature, and time without exceeding quality parameters values it is possible to achieve partial inactivation of spores. Methods used to achieve full inactivation of spores using HPP have yet to

Table 18.1 Application of HPP to fresh-cut fruits and vegetables

Conditions	Results	Author
Fresh-cut pineapple		
200, 270, and 340 MPa; −4 °C, 21 °C, and 38 °C	340 MPa (15 min) for all temperatures tested: ~ 3 decimal reduction: 270 MPa at 38 °C for 15 min: > two decimal reduction: other combinations resulted in no significant reduction	Alemán et al. 1994
270 MPa for 9,000 s	Inoculated with 10^{4-5} CFU g^{-1} *Saccharomyces cerevisiae*, packed in heat-sealed polyethylene pouches, and subjected to static and step pulsed pressure; step pulsed pressure resulted in higher destruction of microorganisms tested	Alemán et al. 1998
Fresh-cut jujube fruit		
600 MPa for 10 min	Could inhibit polygalacturonase (PG) activity and decrease hydrolyzation of non-water-soluble pectin when stored at 4 °C for 9 days	Zong and An 2008
Fresh-cut kiwi		
0.1, 200, 400, and 600 MPa for 10 min	Could effectively kill microorganisms and inhibit PPO activity, but has little influence on firmness of slices and ascorbic acid content	Zong and Zhang 200
Fresh-cut Chinese yam		
600 MPa for 10 min	Effectively prevented browning and microbial growth when stored at 4 °C for 9 days	An and Li 200
Fresh-cut cubes of Granny Smith and Pink Lady apples		
600 MPa for 1–5 min at 22 °C	Vacuum packed in barrier bags with 50 % (v/v) pineapple juice; significantly reduced residual PPO activity	Perera et al. 2010
Packaged fresh-cut melon		
600 MPa for 10 min	Enhancement of β-carotene and minimal loss of sensory properties and health-promoting phytochemicals	Wolbang 2008

be developed. Therefore, there is a need to develop and standardize HPP proces parameters for fresh-cut products with respect to microbial inactivation. Thi development is essential for the commercial success of this technology.

As shown in Table 18.1, HPP has several advantages as a treatment for fresh-cu fruits and vegetables. HPP allows in-package fresh-cut fruit and vegetable processes that reduce the microbial load and extend the product's shelf life. Wolban et al. (2008) investigated the effect of HPP on the nutritional content of package cut melon. It was proven that HPP enhanced not only microbial inactivation, bu also the level of health-promoting phytochemicals, with a minimal loss of sensoria qualities. Recent findings by Perera et al. (2010) using HPP on fresh-cut apple cube in vacuum packages showed significantly reduced residual activity of polyphenoloxidase (PPO). They reported that a combined treatment of 5 min/HPP and 50 pineapple juice inactivated approximately 40 % PPO in Granny Smith apples. Thi means that HPP treatment has the potential to prevent browning of fresh-cut fruit

This result is in agreement with the finding by An and Li (2007), who found that HPP treatment employed at 600 MPa for 10 min on fresh-cut Chinese yam effectively prevented browning and growth of microorganisms when stored at 4 °C for 9 days. In addition, Zong and An (2008) reported that HPP treatment at 600 MPa for 10 min on fresh-cut jujube fruits successfully inhibited the activity of polygalacturonase (PG) and successfully prevented firmness of jujube pieces associated with a decrease in hydrolyzation of non-water-soluble pectin when stored at 4 °C for 9 days.

Enzymes are inactivated by HPP as a result of the conformational changes taking place in enzyme active sites (Min and Zhang 2005). Several enzymes that are partially responsible for oxidative degradation reactions in fresh-cut fruits and vegetables, such as PPO, lypoxygenase (LOX), pectimethylesterase (PME), have been inhibited by HPP treatment (Garcia-Viguera and Bridle 1999; Garzon and Wrolstad 2002). However, during HPP application, it should be pointed out that the residual potent activity or the activation of endogenous enzymes depends on the pressure, temperature, and time at which HPP is applied (Del Pozo-Insfran et al. 2007).

The critical process factors in HPP include pressure, time at pressure, time to achieve treatment pressure, decompression time, treatment temperature (including adiabatic heating), initial product temperature, vessel temperature distribution at pressure, product pH, product composition, product water activity, packaging material integrity, and concurrent processing aids (Hui and Nip 2004).

Although currently only a small number of commercial HPP-treated fresh-cut fruits and vegetables is available, surveys show that demand for these products is increasing, in line with the growth in the number of food companies adopting this HPP technology in Europe and North America. Lastly, HPP has proven to be applicable to fresh-cut fruit and vegetable products in order to extend product shelf life and to achieve product safety without altering the freshlike quality and nutrition of the products.

18.5 Pulsed Electric Fields

Pulsed electric fields (PEFs) have been used as an alternative to heat pasteurization for processing real food systems, including fruit and vegetable tissues (Knorr and Angersbach 1998). A number of experiments have been conducted to study the mechanism and safety of microbial inactivation under PEF treatment (Buchanan et al. 1998; Jin et al. 2001; Raso et al. 1998). Membrane permeability (i.e., damage to cell membranes) has been proposed as the causative factor behind microbial inactivation (Harrison et al. 2001). Another approach was reported by Harrison et al. (1997) in which damaged organelles and lack of ribosomes after PEF treatment are viewed as an alternative inactivation mechanism. However, research or application of this approach using fresh-cut fruits or vegetables as a medium for inactivation of the bacteria is very limited.

In terms of enzyme inactivation mechanisms, extensive studies of PEF have been conducted (Giner et al. 2001). Some studies have used fruits and vegetables as media for the inactivation of enzymes. Changes in enzyme conformational structure specifically have been reported by several authors (Ho et al. 1997; Vega-Mercado et al. 1995). Further, enzymes have different sensitivities to PEF treatments, and many factors influence PEF enzymatic inactivation (Yeom and Zhang 2001).

Some of the technical drawbacks in PEF application that have been further discussed by Barbosa-Cánovas et al. (1999) include residual activity of enzymes and breakdown of food. Textural changes with PEF treatment such as tissue softening in apples, potatoes, and carrots have been reported by Lebovka et al. (2004). The tissue-softening effect of PEF, based on cell membrane electropermeabilization and loss of turgor (Fincan and Dejmek 2003), can be utilized to reduce the energy required for cutting plant material as well as to enhance juice extraction. Therefore, PEF technology is mainly intended for the preservation of pumpable fluids (Hui and Nip 2004; Qin et al. 1996), predominantly fruit and vegetable juices (Min et al. 2003; Heinz et al. 2003). In fact, the adoption of PEF for commercial nonthermal pasteurization of fruit juices was first implemented by Genesis Juice, Springfield and Eugene, OR, USA (Clark 2006).

The results of PEF inactivation of microorganisms and enzymes have been encouraging, suggesting that this technology is an alternative nonthermal method for processing fruits and vegetables (Barbosa-Cánovas et al. 1997). However, for shelf-life extension of fresh-cut fruits and vegetables, PEF technology alone seems far from promising, as it is highly recommended that PEF be combined with other preservation methods.

18.6 Irradiation

Irradiation of food is not a new idea. It has been established as a safe and effective method of food processing and preservation after more than five decades of research and development (Korkmaz and Polat 2005). Irradiation literally means exposure to radiation (Grandison 2006). Food irradiation is a physical treatment in which food is exposed to ionizing radiation, i.e., radiation of sufficient energy to expel electrons from atoms and ionize molecules (Niemira and Deschenes 2005). Irradiation is a nonthermal technology or *cold process* because foods increase by only a few degrees from the radiation energy absorbed, even at the higher doses used for sterilization. Consequently, irradiation treatment causes minimal changes in appearance and provides good nutrition.

This technology has been used to eliminate foodborne pathogens and natural contaminants from fresh fruits and vegetables (Thayer and Rajkowski 1999). The mechanism of decontamination by irradiation is that it directly harms the genetic material of the living cell, leading to mutagenesis and eventually to cell death (Barkai-Golan 2001). Irradiation affects microorganisms such as bacteria, yeasts, and molds by causing lesions in the genetic material of cells, effectively preventing he cells from carrying out the biological processes necessary for continued cell existence (Rahman 1999). Irradiation can reduce the incidence of pathogenic microorganisms associated with fresh-cut products without changing the minimally processed character of the products (Farkas et al. 1999). Thus, irradiation is one of he potential effective technologies that can inactivate foodborne pathogens in fresh-cut fruits and vegetables.

The U.S. Food and Drug Administration (FDA) approved the use of irradiation on wheat and potatoes in 1963; on spices, pork, fruits, and vegetables in the 1980s; poultry in the early 1990s; and red meats in (beef, veal, lamb) (Majchrowicz 1999). In accordance with international regulations such as the *Codex Standards for Food Irradiation*, the ionizing radiation permissible for irradiating foods, including fruits and vegetables, is limited to (a) gamma rays from radioisotope Cobalt 60 or Cesium-137, (b) x-rays generated from machine sources operated at or below an energy level of 5 MeV, and (c) electrons generated from machine sources operated at or below an energy level of 10 MeV (Lacroix et al. 2003; Sharma 2004).

Table 18.2 shows that low-dose irradiation has been successfully applied for extending the shelf life of many fresh-cut products. Several investigators have proven that irradiation can be a suitable method for extending shelf life while ensuring product safety by inactivation of microorganisms on fresh-cut fruits and vegetables (Buchanan et al. 1998; Hagenmaier and Baker 1997).

Lu et al. (2005) reported that fresh-cut celery treated with low-dose gamma irradiation has more vitamin C, soluble solids, and total sugars, as well as better sensory quality, than that of nonirradiated celery. They summarized that low-dose gamma irradiation, 1 kGy, was successfully utilized to extend the shelf life and ensure the safety of fresh-cut celery. Irradiation has also been applied to fresh-cut carrots stored in microporous bags, resulting in limited respiration increase due to wounding and reduced ethylene production and increasing the shelf life of the product (Chervin et al. 1992).

Many other researchers have reported the successful application of irradiation as an effective method to extend the shelf life of fresh-cut products, as summarized in Table 18.2. Application of irradiation on fresh-cut products is very dependent on the dose of irradiation. At higher doses, a higher reduction in microbiology as well as higher rate of destruction of the quality of fresh-cut plant products have been observed. As shown in Table 18.2, irradiation doses should be kept as low as possible to achieve the safe quality of products and extend their shelf life without decreasing their organoleptic quality. Grandison (2006) stated that overdoses of irradiation generate textural problems resulting from radiation-induced depolymerization of cellulose, hemicellulose, starch, and pectin, leading to the softening of tissue. Other dose-dependent disorders include discoloration of skin, internal browning, and increased susceptibility to chilling injury, although nutrition losses are minimal. Some studies have also shown that ionizing radiation can cause the development of an off-odor (Spoto et al. 1997).

The main issue with this technology is the unfavorable image or public perception of irradiated food. Nevertheless, low-dose irradiation is considered to have high potential and is probably one of the most successful and versatile processes for

Table 18.2 Application of low-dose irradiation for extending shelf life of fresh-cut fruits an vegetables

Dosage	Results	Author
Fresh-cut lettuce		
1.0 kGy	Number of aerobic mesophyllic bacteria was reduced by 2.35 log; sensory quality was maintained best during storage for 8 days at 4 °C	Zhang et al. 200
0.5 and 1.0 kGy	Similar firmness and vitamin C and antioxidant contents to that of controls after 14 and 21 days of storage	Fan et al. 2003
0.19 kGy	8 days after irradiation microbial population was much lower compared to nonirradiated sample	Hagenmaier and Baker 1997
0.15, 0.38, or 0.55 kGy	5 log reduction in *E. coli* counts and lack of adverse effects on sensory attributes, indicating that low-dose irradiation can improve the safety and shelf life of fresh-cut iceberg lettuce for retail sale or food service	Foley 2002
1.0 kGy	Eliminated bacterial contamination from lettuce sample without any sensorial quality defects	Kim 2006
1.0, 1.5 and 3.2 kGy	Potential fungicidal effect of low-dose irradiation (1.0 kGy) on packaged romaine lettuce hearts without altering overall quality	Han et al. 2004
0.3–1.2 kGy	1.15 and 0.51 kGy with subsequent refrigerated storage (4 °C) reduced inoculated-microbial populations by > 5 and > 2 log, respectively	Mintier and Fole 2006
Fresh-cut romaine and iceberg lettuce and endive		
0, 0.5, 1.0, and 2.0 kGy	Irradiation increased phenolic content and antioxidant capacity of both tissue types in all vegetables at days 4 and 8 at 7–8 °C	Fan 2005
Fresh-cut cantaloupe		
1.0, 1.5, and 3.1 kGy	Samples irradiated at dose levels 1.0–1.5 kGy had better quality attributes than nonirradiated samples	Castell-Perez et al. 2004
Up to 1.5 kGy	Irradiated samples resulted in a much higher reduction, 3 log TPC number; shelf life was extended by up to 11 days of storage	Boynton et al. 2005
0.5 and 1.0 kGy	Color and texture remained stable after 20 days of storage; low-dose irradiation may increase shelf life while maintaining high product quality	Boynton 2004
0.5 kGy	Low microbial load similar to that of cubes prepared from hot-water-treated fruit	Fan et al. 2006
0.7 and 1.4 kGy	Irradiation reduced total aerobic microbial counts with increasing doses	Palekar et al. 2004
Up to 10.0 kGy	D10 values of Poliovirus Type 1 and MS2 bacteriophage were 4.76 and 4.54 kGy, respectively; results suggest that E-beam irradiation can be used to destroy enteric viruses on cantaloupe surfaces	Pillai et al. 2006
1.0 and 3.0 kGy	1.0 kGy caused 2–3 log reductions in microbial counts; Brix, pH, and sensory attributes were also unaffected	Horrick 2002
Fresh-cut apple		
Up to 5.0 kGy	Threshold for maintaining firmness of sliced apples was 0.34 kGy	Gunes et al. 2001

(continued)

Table 18.2 (continued)

Dosage	Results	Author
0.5 and 1.0 kGy	Enhanced microbial food safety while maintaining quality of fresh-cut apple slices	Fan et al. 2005
1.6 kGy	Did not significantly affect color, soluble solid content, titratable acidity, or apple aroma intensity	Fan et al. 2005
1.2 kGy	Doses less than 1.2 kGy had no effect on rates of CO_2 production and O_2 consumption	Gunes et al. 2000
Fresh-cut celery		
1.0 kGy	Number of bacteria and fungi in fresh-cut celery was decreased by orders of 10^2 and 10^1	Lu et al. 2005
0.5 and 1.0 kGy	Sensory shelf life of 1.0 kGy treated celery was 29 days compared to 22 days for control (chlorinated)	Prakash et al. 2000
0.5, 1.0, 1.5, and 2.0 kGy	Dose of 1 kGy reduced bacteria and fungi contamination to acceptable levels without changing acceptability of samples during recommended shelf life (8 days at 5 °C)	López et al. 2005
Fresh-cut green onion		
0.5, 1.0, and 1.5 kGy	Irradiated samples maintained a relatively low decay percentage at 14 days of storage	Kim et al. 2005
1.0 kGy	Reduced aerobic plate counts, yeasts and molds, and psychrotrophic counts by 3–5 log CFU g^{-1} without negatively affecting quality (14 days of storage)	Butris et al. 2003
Fresh-cut tomato		
0.7 and 0.95 kGy	Reduction of 1.8 and 2.2 log10 CFU g^{-1} on tomatoes inoculated with *Salmonella* for 0.7 and 0.95 kGy	Schmidt 2004
Up to 0.9 kGy	D-value ranged from 0.26–0.39 kGy, indicating that a 5 $\log_{10}$ CFU g^{-1} reduction in *Salmonella* spp. in diced tomatoes would require a dose of 1.3–1.95 kGy	Prakash et al. 2007
Fresh-cut (diced) bell pepper and tomato		
Up to 3.7 kGy	Total pectin content in tomatoes and bell peppers remained relatively constant with irradiation during storage for 12 days at 4 °C	Costa et al. 2001
Fresh-cut Chinese cabbage		
up to 2.0 kGy	1–2 kGy ensured microbial safety of minimally processed Chinese cabbage without significant loss in quality for 3 weeks	Ahn et al. 2005
Fresh-cut broccoli head		
1.0, 2.0, and 3.0 kGy	Treatment up to 3 kGy maintains overall quality of fresh broccoli	Gomes et al. 2008
Fresh-cut mint (inoculated with *E. coli* O157:H7, *Salmonella*, and *MS2 bacteriophage*)		
Up to 2.0 kGy	Population decreased up to 5.8 log CFU g^{-1}, and 1.0–2.0 kGy appears promising as a method for improving microbiological quality of fresh mint without compromising visual and color attributes	Hsu et al. 2010
Fresh-cut carrot		
2.0 kGy	Twofold to fourfold increase in shelf life at refrigeration temperature	Kamat et al. 2005

(continued)

Table 18.2 (continued)

Dosage	Results	Author
2.0 kGy	Prevented losses of orange color and carotenes; sensory analysis demonstrated preferences for irradiated vegetables	Chervin and Boisseau 1994
2.0 kGy	Significant reduction in respiration by 50 % and ethylene production by 80 %	Chervin et al. 1992
0.5 kGy	Shredded carrots treated with irradiation had a mean microbial population of 1,300 CFU g^{-1} at expiration date (9 days after irradiation) compared to 87,000 CFU g^{-1} for nonirradiated, chlorinated controls	Hagenmaier and Baker 1998
Fresh-cut carrot, cucumber, lettuce, mixed vegetable salad, green bean, celery, mixed peas diced carrots, and fruits (pear and apple)		
Up to 6.0 kGy	Large reduction in microbial counts, shelf-life extension, and elimination of foodborne pathogens without impairing quality, at following doses: 1.5 kGy for celery (14 days of storage); 2 kGy for lettuce, green beans, apples, pears (15 days of storage); 3 kGy for cucumbers, mixed vegetables salad, mixed peas with diced carrots (15 days of storage); and 4 kGy for carrots (21 days of storage)	Hammad et al. 2006
Fresh-cut fruits (pineapple, jackfruit, mixed fruits) and vegetables (onion and cucumber)		
0.0–3.0 kGy	Low-dose irradiation eliminated or reduced risk of foodborne pathogens and did not affect the color (lightness, redness and greenness) of minimally processed onion and cucumber	Faridah et al. 2006
Polyethylene packaged fresh-cut cucumber, tomato, carrot, cabbage, apple, melon, cauliflower, bitter gourd		
Up to 2.5 kGy	Maintained shelf life for 2 weeks at refrigerated temperature: 2 kGy for carrots, 1.5 kGy for cauliflower and 2.5 kGy for apples, cucumber and cabbage; 1 week shelf life at refrigerated temperature: 2.5 kGy for tomato, 2 kGy for bitter gourd, and 1 kGy for melon	Bibi et al. 2006
Fresh-cut coriander, lettuce, mint, parsley, turnip, watercress, melon, and watermelon inoculated with *E. coli* 0157:H7 and *L. innocua*		
Up to 1.0 kGy	No important differences were found overall in sensory and physicochemical properties after irradiation up to 1 kGy	Trigo et al. 2006
Fresh-cut (shredded) carrot, mixed salad samples (radicchio and butterhead lettuce), red leaf lettuce, green lettuce and soybean sprouts (inoculated with *L. monocytogenes*, *E. col* 0157:H7, and *Salmonella*)		
1.0–1.5 kGy	Inactivation of pathogens, no effect on sensory attributes during storage	Basbayraktar et al. 2006
Fresh-cut ready-to-use vegetables: cucumber, blanched and seasoned spinach (inoculated with *Salmonella typhimurium*, *E. coli*, *Staphylococcus aureus*, and *L. ivanovii*)		
Up to 3.0 kGy	Low-dose irradiation (3 kGy or less) can improve microbial safety of ready-to-use vegetables	Young Lee et al. 2006
Fresh-cut cauliflower		
1.5 kGy	Treatment maintained quality of fresh-cut cauliflower	Nunes et al. 200

(continued

Table 18.2 (continued)

Dosage	Results	Author
Fresh-cut red beet		
1.0 or 2.0 kGy	Pigments seemed to overcome irradiation dose of 1 kGy	Latorre et al. 2010
Fresh-cut witloof chicory		
3.0 kGy	Irradiation-induced browning of cut chicory may be due to increased phenolic metabolism and reduced antioxidant capacities; increased membrane permeability may also allow substrate-enzyme contact after 5 days of storage at 10 °C	Hanotel et al. 1995

application in the commercialization of fresh-cut products; however, its application on food is conditional and regulated based on the appropriate dose levels. Other factors associated with this technology are the initial capital investment and operational costs

18.7 Ozone

Washing is a critical step in processing fresh-cut fruits and vegetables. Generally, chlorine is used to sanitize fruits and vegetables in fresh-cut processing. However, the use of chlorine is questionable because of the possible formation of carcinogenic chlorinated compounds in water. The use of ozone as an alternative sanitizer to chlorine is attracting more interest (Guzel-Seydim et al. 2004). There are a number of reviews about the utilization of ozone technology in food processing (Kim et al. 2003; Khader et al. 2001) and, in particular, fresh-cut processing (Strickland et al. 2010). Ozone, with its high oxidizing power, is considered to be a strong antimicrobial agent with high reactivity and thus is applicable in ensuring the microbial safety of raw produce (Khader et al. 2001). Due to its instability, ozone does not produce persistent disinfection residuals (Kim et al. 2003). The spontaneous autodecomposition of a nontoxic product in the absence of ozone residue is one of the advantages of using this nonthermal technology.

Ozone technology has long been used as a treatment for drinking water (Muthukumarappan et al. 2000) and was deemed Generally Recognized As Safe (GRAS) in July 1997 by an independent panel of scientists (Majchrowicz 1999). Fruits and vegetables have the advantage of having smooth surfaces with low ozone demand (Khader et al. 2001), making them potentially and particularly suitable for aqueous ozone treatments. Ozone-sanitized fresh produce has recently been introduced in markets in the USA (Artés and Allende 2005), and numerous researchers have also focused on ozone application to other fresh-cut products (Table 18.3).

Table 18.3 Ozone application studies on fresh-cut fruits and vegetables (O_{3A} = aqueous O_3, O_{3G} = gaseous O_3)

Conditions	Results	Author
Fresh-cut lettuce		
0.5–4.5 ppm O_{3A} for 0.5–3.5 min	2 ppm O_{3A} treatment for 2 min was optimal for O_3 disinfection of *L. monocytogenes* on green leaf lettuce, sensory quality during cold storage	Ölmez and Akbas 2009
1.11 and 1.15 mg L^{-1} O_{3A} for 2 min pre-washing	1 mg L^{-1} was too low to achieve germ reduction of trimmed lettuce heads, unlike that achieved with 200 mg L^{-1}chlorine for 2 min common in commercial practice	Baur et al. 2004
0–10 mg L^{-1} O_{3A} in cold water (2 °C) in ice–slurry system	3 mg L^{-1} O_{3A} was optimal, causing 3–4 log unit in reductions of microorganisms, similar to results achieved with 100 mg L^{-1} chlorinated water	Kim 2006
5 ppm O_{3A} for 5 min	Reduction of microbial count by 1.8 log units	Selma 2007
4 mg L^{-1} O_{3A}	Reduction of mesophilic and psychrotrophic bacteria by 1.7 and 1.5 $\log_{10}$ CFU g^{-1}, respectively	Akbas and Ölmez 2007
10, 20, and 10 mg L^{-1} O_{3A} at 4 °C and UV	O_{3A} could be an alternative sanitizer to chlorine for fresh-cut lettuce due to good retention of sensory quality and browning control with no detrimental reduction in antioxidant constituents	Beltran et al. 2005
Aqueous O_3 (3, 5, and 10 ppm)	Bacterial reduction of 1.4 log CFU g^{-1} up to 5 ppm aqueous O_3	Koseki and Isobe 2006
1, 3, and 5 ppm O_{3A} for 0.5, 1, 3, or 5 min	1.09 and 0.94 log reductions of *E. coli* O157:H7 and *L. monocytogenes*, respectively	Yuk et al. 2006
1 mg L^{-1} O_{3A} at 18–20 °C	Enzymatic activity decreased significantly	Rico et al. 2006
O_{3A} at 4 °C for 6 days	Industrial trial: O_3 generator was integrated into a commercial lettuce-washing facility; quality of lettuce during storage was unaffected; only limited destruction in microbial population	Hassenberg et al. 2007
Fresh-cut celery		
O_{3A} at different doses	0.18 ppm O_{3A} dipp resulted in highest reduction of microbial population	Zhang et al. 2005
Fresh-cut cilantro		
O_{3A} followed by AcEW or chlorine wash	Sequential wash is effective in reducing initial total aerobic plate count and maintaining relatively low microbial count; O_{3A} treatment effectively maintained typical aroma and overall quality of fresh-cut cilantro leaves	Wang et al. 2004
Fresh-cut cantaloupe		
10,000 ppm O_{3G} for 30 min	Treatment reduced total mesophilic and psychrotrophic bacteria and mold counts by 1.1, 1.3, and 1.5 log units, respectively; combination of hot water and O_{3G} was most	Selma et al. 2008

(continued)

Table 18.3 (continued)

Conditions	Results	Author
	effective in controlling microbial growth, achieving 3.8, 5.1, 2.2, and 2.3 log reductions for mesophilic and psychrotrophic bacteria, molds, and coliforms, respectively	
0.4 mg L^{-1} O_{3A} combined with peracetic acid	O_{3A} for 3 or 5 min had lower efficiency in reducing microbial count; nevertheless, the combination of peracetic acid with O_{3A} (3 min) was effective at reducing microbial count and maintaining antioxidant compounds such as vitamin C and DPPH	Silveira et al. 2010
10,000 ppm O_{3G} for 30 min under vacuum	Reduction and spoilage of fresh and fresh-cut melon	Selma et al. 2008
Fresh-cut onion, escarole, carrot, and spinach		
O_{3G} flow of 80 mg min^{-1}	O_{3G} flow was effective in reducing microbial counts of bacteria, molds, and yeasts; maximum total microbial reductions achieved 5.9 log CFU mL^{-1}	Selma et al. 2008
Fresh-cut broccoli		
1 ppm O_{3A}	50 min O_{3A} treatment reduced microorganisms better, compared to 10 min treatment, and did not influence quality parameters	Zhuang et al. 1996
O_{3A}, tap water, chlorinated water, and electrolyzed water	O_{3A} for 90 s was not very effective in reducing microbial population compared to chlorinated and electrolyzed water; however, samples washed with O_{3A} for 180 s showed the lowest number of total aerobic and coliform plate counts	Das and Kim 2010
Fresh whole and fresh-cut (sliced) tomato		
4 mu L L^{-1} O_{3A} applied cyclically for 30 min every 3 h	Bacteria: 1.1–1.2 log reduction Fungi: 0.5 log reduction O_3 caused no damage or off-flavor in sliced or whole tomatoes	Aguayo et al. 2006
Fresh-cut green asparagus		
1 mg L^{-1} O_{3A}	Enzyme activity inhibited	An et al. 2007
Fresh-cut baby leaf *Brassica* species (salad rocket, wild rocket, mizuna, and watercress) stored at 1 °C, 4 °C, 8 °C, and 12 °C		
10 mg L^{-1} O_{3A} and UV	O_{3A} combined with UV was the most efficient washing treatment in reducing total mesophyllic count; heat shock treatment was ineffective	Martínez-Sánchez et al. 2008
Fresh-cut green bean and bell pepper		
2 ppm O_{3A}	Peroxidase inactivation, color of vegetables unaffected	Elisabete and Joana 2006

As shown in Table 18.4, extending shelf life and preserving the freshlike quality of fresh-cut products can be achieved by ozone treatment, particularly in the form of aqueous ozone.

Ozone dissolved in water is a thermodynamically ideal condition, as expressed in the following equation:

$$Cs = \beta M \times P\gamma, \tag{18.4}$$

where Cs is the saturation concentration (kg O_3 m^{-3} water), β (absorption coefficient) is the volume of ozone dissolved per unit volume of water (at a given temperature) in the presence of equilibrating ozone at 1 atm pressure, M is the mass volume of ozone (kg m^{-3}), and $P\gamma$ is the partial pressure of ozone in the gas phase (Bablon et al. 1991 cited in Khader et al. 2001). In practical terms, dissolution of ozone in water can also be expressed in the solubility ratio (Sr) as follows:

$$\mathrm{Sr} = \frac{\text{mg L}^{-1}\ \mathrm{O_3}\ \text{in water}}{\text{mg L}^{-1}\ \text{in the gas phase}}. \tag{18.5}$$

An excellent assessment of microbial inactivation by aqueous ozone has been reviewed by Khader et al. (2001). According to Zambre et al. (2010), the longer shelf life of ozone-treated samples is mainly due to a reduction in surface microbial count. Ozone is considered to be an efficient decontamination agent for fresh products, demonstrating a broad-spectrum bactericidal attack on the bacterial cell wall and outer cell membrane (Bialka et al. 2008). The antimicrobial action of ozone is due to the strong oxidizing activity of either the molecular ozone itself or its decomposition products. As shown in Table 18.3, ozone was effective in eliminating inoculated microorganisms and extending shelf life, for example, fresh-cut lettuce inoculated by *Listeria monocytogenes* (Ölmez and Akbas 2009) and *Escherichia coli* O157:H7, *Salmonella enterica serovar Typhimurium L. monocytogenes*, and *Staphylococcus aureus* (Kim et al. 2006). A low level o ozone (2–3 ppm) for short exposure times (2–5 min) was found to be an optimu processing condition for disinfection of fresh-cut lettuce in terms of reducin microbial load and maintaining sensory quality. Furthermore, Olmez and Akba (2009) reported that ozone treatment was found to be more effective than chlorin and organic acid treatments in maintaining sensory quality.

Kim et al. (1999) concluded that ozone is more efficient at lower concentration and shorter treatment times than more standard sanitizers, including chlorine. Sing et al. (2002) reported that gaseous treatments of ozone were more effective tha aqueous ozone in reducing *E. coli* O157:H7 on lettuce. Similar results were als reported by Bialka and Demirci (2007) in which reductions of *E. coli* O157:H7 an *Salmonella* were achieved on blueberries treated with gaseous ozone, among othe treatments, and by Akbas and Ozdemir (2008), who found that a decreasing numbe of *E. coli* and *Bacillus cereus* cells treated with gaseous ozone was achieved at lo concentrations. Moreover, Klockow and Keener (2009) reported that ozone has th

Table 18.4 Extending shelf life of fresh-cut fruits and vegetables using UV light

Conditions	Results	Author
Fresh-cut apple		
5.6, 8.4, and 14.1 kJ m^{-2} for 10, 15, and 25 min	Breakage of cellular membranes in UV-treated samples; lower microbial count compared to untreated samples	Gómez et al. 2010
13.8 W m^{-2} for 5 min at 4 °C	Enzyme inactivation was limited to a thin surface layer without affecting interior of tissue	Manzocco et al. 2009
Fresh-cut Tommy Atkins mango		
250–280 nm UV for 10 min	Improvement in total antioxidant capacity of fresh-cut mango	Gonzalez-Aguilar et al. 2007
Fresh-cut baby spinach leaves		
Double-sided UV (2.4–24 kJ m^{-2})	At low doses, UV was effective in reducing initial psychrotrophic and *enterobacteria* counts and kept *L. monocytogenes* at low levels during storage without affecting sensory quality	Escalona et al. 2010
Fresh-cut watermelon		
4.1 kJ m^{-2}	In commercial trials, exposing packaged watermelon cubes to UV produced a > 1 log reduction in microbial populations by end of product shelf life without affecting juice leakage, color, or overall visual quality	Fonseca and Rushing 2006
1.6, 2.8, 4.8, and 7.2 kJ m^{-2}	No significant effect on vitamin C content; catalase activity and total polyphenol content declined considerably throughout storage	Artés-Hernández et al. 2010
Fresh-cut tropical fruits: honey pineapple, banana *pisang mas*, and guava		
2.1 J m^{-2} for 10, 20, and 30 min	Increase in total phenol and flavonoids, decrease in vitamin C	Alothman et al. 2009
Fresh-cut cantaloupe		
UV (254 nm) for 15 and 60 min	Increase concentrations of terpenoids in cantaloupe tissue	Beaulieu 2007
Fresh-cut (tissue slices) zucchini squash		
UV (250–280 nm) for 1, 10, and 20 min	Delay of senescence and deterioration in tissues, reduction in microbial population, improved storage quality	Erkan et al. 2001
Fresh-cut spinach leaves		
4.54, 7.94, and 11.35 kJ m^{-2}	Low to moderate UV can be an effective alternative to sanitizing with chlorine for minimally processed spinach leaves and can preserve quality	Artés-Hernández et al. 2010
Fresh-cut pear		
Up to 87 kJ m^{-2}	Large log reduction rates were observed at doses between 0 and 15 kJ m^{-2}	Schenk et al. 2008
Fresh-cut tomato		
3.2–19.2 kJ m^{-2}	Reduction in development of microbial populations, increased phenolic content, and delayed degradation of vitamin C after 7 days of storage at 4–6 °C	Kim et al. 2008

(continued)

Table 18.4 (continued)

Conditions	Results	Author
Fresh-cut pineapple		
UV for 15 min, 1–2 cm^2 slices	UV Fotodyne Model 3–3000 Transilluminator (Fotodyne, Hartland, WI, USA); UV-induction of phytoalexin compounds in pineapple; potential use of UV to elicit natural defense mechanisms of fresh-cut fruits	Lamikanra and Richard 2004

capability of reducing *E. coli* O157:H7 in packaged spinach (3–5 log cfu per leaf) with low concentrations (1.6 and 4.3 ppm) for short exposure (5 min).

Indeed, ozone technology for shelf-life extension of fresh-cut salad mix products has been applied successfully since 2000 by Strickland Produce (Strickland et al. 2010). Significant improvements in product quality, plus savings in water and labor, were achieved by the company with the recovery of its investment in ozonation in less than 2 years. As with much of the newest information related to ozone application and regarding the relatively lower capital cost compared to irradiation, commercial use of ozone systems for fresh-cut fruits and vegetables, in particular for sanitizing systems, is applicable.

18.8 Ultraviolet Radiation

Excellent reviews about the benefits and adequacy of ultraviolet (UV) light processing in food applications have been published by several authors (Guerrero-Beltrán and Barbosa-Cánovas 2004). Book chapters on ultraviolet processing of food are also available (Lopez-Malo and Palou 2005). Bintsis et al. (2000) indicated that some companies use UV-treated water in the decontamination of fresh produce such as shredded lettuce. Utilization of UV light in the food industry has several advantages over other agents because it leaves no residue, does not affect moisture and temperature, and is economical. Another advantage is that no excessive protection for workers is necessary and there is no residual radioactivity, even at high levels of exposure (Bintsis et al. 2000).

Microbial inactivation with UV light is a well-known surface treatment. For that reason, the technology has been more applied on the surface of fresh-cut fruits and vegetables than in liquid plant products (Bermudez-Aguirre and Barbosa-Cánovas 2011). The microbial cell surface has been suggested as the primary target of UV treatment. Inactivation is caused by the cross-linking of thymine dimers of cell DNA, thus preventing repair and reproduction (Sizer and Balasubramanian 1999). The effectiveness of microbial disinfection with UV light in extending the shelf life of fresh-cut products depends on several factors, including product profile, wavelength, transmissivity of the product, geometric configuration of the reactor, and radiation path length (Hui and Nip 2004). High UV doses may promote damage to the treated tissue (Rico et al. 2007), and in certain plants UV can easily cause off-flavors (Ohlsson and Bengtsson 2002).

The decrease in intensity when monochromatic UV light is transmitted through the medium is described by the Lambert-Beer law:

$$I = Io.e^{ad}, \tag{18.6}$$

where I is the attenuated intensity, Io is the incident monochromatic UV intensity, and d is the depth reached by the UV light (Guerrero-Beltrán and Barbosa-Cánovas 2004).

Survival of inoculated microorganisms after UV treatment in fresh-cut samples is measured by the first-order kinetics model describing the relationship between survival microorganisms and doses, based on the following equation:

$$log\frac{N}{No} = -kD, \tag{18.7}$$

where No is the initial concentration of microorganisms, N is the concentration of microorganisms after UV treatment, k is a constant, and D is the dose (J m^{-2}) (Chang et al. 1985). Another mathematical model has been described as follows:

$$ln\frac{N}{No} = -kIt, \tag{18.8}$$

where N is the number of survival microorganisms after UV radiation, No is the initial load of microorganisms, k is a constant that depends on the type of microorganisms and environmental conditions, I is the intensity (W m^{-2}), and t is the exposure time (s) (Stermer et al. 1987).

The application of UV radiation in extending the shelf life of fresh-cut vegetables has generated numerous studies (Table 18.4) describing the effects of UV radiation on fresh-cut products. Recent research by Artés-Hernández et al. (2010) concluded that UV radiation is a promising tool for maintaining the overall quality of fresh-cut watermelon. Additional findings were reported by Artés-Hernández et al. (2010), who found that low to moderate UV radiation could be used in preserving the quality of minimally processed spinach leaves instead of using chlorine as a sanitizer. Another successful finding has been reported by Lamikanra et al. (2005), who indicated that UV radiation could improve the shelf life and quality of fresh-cut cantaloupe melon. Application of low-dose UV light has been shown to be effective against common foodborne pathogens (Sastry et al. 2000). Additionally, Yaun et al. (2004) found that low-dose UV has a strong beneficial effect on the microbial safety of fresh-cut fruits and vegetables in compliance with Good Agricultural Practices and Good Manufacturing Practices.

Allende et al. (2006) reported that at low-dose two-sided UV radiation, 1.18, 2.37 and 7.11 kJ m^{-2} were effective in reducing the natural microflora of fresh-cut lettuce and therefore UV could improve the shelf life of minimally processed red oak leaf lettuce without compromising quality. Meanwhile, Vicente et al. (2005) suggested that UV treatments could be useful in reducing tissue decay and maintaining the quality of fresh-cut bell peppers. Furthermore, they explained that the incidence and severity of chilling injury could be reduced by short UV treatments. Kasim et al. (2008) found that UVC at a low dose may control the rate of decay in fresh-cut green onions and preserve fresh-like quality. Exposure to UV also may enhance the synthesis of bioactive compounds; for example, UVC irradiation appears to be a good technique to improve the total antioxidant capacity of fresh-cut mango. Similar results have been reported by Lamikanra and Richard (2004) who found that UV-treated fresh-cut pineapple induced production of phytoalexin compounds, demonstrating the potential use of UV radiation to elicit natural defense mechanisms in fresh-cut fruits, which could also enhance the shelf life of fresh-cut pineapple. Finally, these examples and a commercial trial by Fonseca and Rushing (2006) demonstrating shelf life extension of fresh-cut products show that appropriate UV radiation dosage has a positive advantage in providing more ideal fresh-cut products with fresh-like characteristics.

18.9 Ultrasound

Investigation of ultrasound has recently been introduced for preservation purposes in food processing due to its ability to inactivate microorganisms without the deleterious effects of heat on the flavor, color, and nutrition of food (Piyasena et al. 2003). Ultrasound consists of "elastics waves" with frequencies that are above the threshold of human hearing (≅ 20 kHz) (Mulet et al. 2002).

The bacterial inactivation effect of ultrasound has long been observed [Harvey and Loomis 1929, cited in Feng and Yang (2006)]. The mechanical effects of power ultrasonics are mainly attributed to cavitation, whose forces have a dramatic effect on biological systems (Mason and Paniwnyk 2003). The inactivation effect of ultrasound has also been attributed to intracellular cavitation; these mechanical shocks can disrupt cellular structural and functional components to the point of cell lysis (Butz and Tauscher 2002).

As summarized in Table 18.5, ultrasound is applied to fresh-cut products to reduce the initial microbial load and inhibit endogenous enzymes of minimally processed fruits and vegetables. Seymour et al. (2002) investigated the effectiveness of power ultrasound (25–70 kHz) on the microbial decontamination of minimally processed fruits and vegetables for iceberg lettuce, whole cucumber, cut baton carrot, capsicum pepper, white cabbage, spring onion, strawberry, curly leaf parsley, and mint and other herbs. They reported that ultrasound treatment in the range 25–70 kHz does not completely eliminate the risk of pathogens on fresh-cut products. Zhou et al. (2009) concluded that ultrasonication enhanced the reduction of *E. coli* cells on spinach in all treatments (0.7–1.1 log) over that of washing with a sanitizer alone.

Table 18.5 Ultrasonic application on fresh-cut fruits and vegetables

Condition	Results	Author
Fresh-cut apple		
40 kHz with 1 % ascorbic acid	In combination with ascorbic acid had positive effect on maintaining quality	Jang et al. 2009
Fresh whole spinach leaves		
21.2 kHz	Significant reduction of *E. coli* cells on spinach in all treatments by 0.7–1.1 log compared to washing with a sanitizer alone	Zhou et al. 2009
Fresh-cut apple and lettuce (inoculated with *Salmonella* and *E. coli* O157:H7)		
Combined with chlorine decontamination	Treatment time can be increased to bring temperature to sublethal point without damaging the food, increasing decontamination efficacy	Huang et al., 2006
Fresh-cut Royal Gala apples and romaine lettuce (inoculated with *E. coli* O157:H7 and *Salmonella*)		
120 and 170 kHz	Combination with chlorine dioxide increased decontamination	Xu 2005
Fresh-cut fruits and vegetables (iceberg lettuce, whole cucumber, cut baton carrot, capsicum pepper, white cabbage, spring onion, strawberry, curly leaf parsley, mint and other herbs) inoculated with *Salmonella typhimurium*, *L. monocytogenes*, and *E. coli*		
25, 32–40, and 62–70 kHz for 30 min	Frequency of ultrasound treatment had no significant effect on decontamination efficiency	Seymour et al. 2002

Recently, the effects of ultrasound treatment on fruit decay and the physiological quality of strawberries were described by Cao et al. (2010), who reported that a 40 kHz ultrasound treatment resulted in a significant decrease in decay incidence and number of microorganisms. Further, the fresh quality of strawberries was maintained in terms of firmness, total soluble solids, vitamin C, and titratable acidity. The researchers concluded that ultrasound treatment possessed the potential ability to extend the shelf life and maintain the quality of strawberries. In addition, the use of ultrasound in combination with ascorbic acid on fresh-cut apples inhibited 98 % of PPO enzymes (Jang et al. 2009). It was shown that ultrasound technology could inhibit microorganisms and enzymes, prolonging the shelf life and maintaining the quality of fresh-cut apples. However, other studies have shown relatively low inactivation of microorganisms and enzymes (Sala et al. 1999); therefore, it is widely accepted that ultrasound alone is not an effective method for inactivating bacteria in food (Piyasena et al. 2003). In combination with acid (i.e., ascorbic acid) or mild heat, pressure, and other nonthermal processes, power ultrasound has a synergistic effect on inactivation and may be relatively more effective for pathogen removal and inactivation. Also, these combination treatments may help to prolong shelf life and retain the quality of fresh produce, such as retention of vitamins and other heat-sensitive ingredients.

18.10 Acidic Electrolyzed Water

Acidic electrolyzed water (AcEW) is a new concept technology that was developed in Japan and has been classified as so-called functional water. Some scientists use the alternative term electrolyzed oxidizing water (EOW) (Al-Haq et al. 2005), while at present the term neutral electrolyzed water (NEW) has gained more interest. This technology offers the potential ability to inactivate microorganisms with minimal effects on nutritional content. For this reason the application of electrolyzed water on foods such as fresh-cut products in particular is currently a subject of major interest for food decontamination as an alternative to chlorine decontamination. To date, electrolyzed water has been applied on fresh-cut fruits and vegetables, mainly as a washing and disinfection agent to reduce the level of microorganism contamination to ensure food safety and extend shelf life. Washing and disinfection are major critical steps in the processing chain for fresh-cut fruits and vegetables.

EOW production requires only water and salt (sodium chloride). EOW has the following advantages over other traditional cleaning agents: effective disinfection, practicality, relatively low expense, and environmental friendliness. The main advantage of EOW is its safety. EOW, which is also a strong acid element, is different from hydrochloric acid or sulfuric acid in that it is not corrosive to the skin, mucous membranes, or organic material. Electrolyzed water has been tested and used as a disinfectant in the food industry and other applications (Huang et al. 2008).

The utilization of this technology on fresh-cut fruits and vegetables by microbial decontamination is summarized in Table 18.6.

Unfortunately, research on the impact of this technology on enzyme inactivation is scarce. Most of the described studies were carried out in laboratory settings only for microbial disinfection. Koseki et al. (2001) suggested the use of electrolyzed water for controlling microorganisms for plant products as an alternative to chlorine sanitizer. Moreover, Bari et al. (2003) concluded that acidic electrolyzed water could be useful in controlling pathogenic microorganisms. Very interesting results were obtained by Achiwa et al. (2004) in the bacterial inactivation of fresh-cut salads treated with acidic electrolyzed water. AcEW has a considerable effect on higher initial bacterial counts in salad products (without packaging), but when applied to takeout sealed packaged products, this treatment was not very effective, although reduction in the number of bacteria was noted. However, a recent finding by Issa-Zacharia et al. (2010) indicated that AcEW can potentially reduce the amount of *E. coli* and *S. aureus* cell contamination within a short period of time, which makes it a potential replacement for NaOCl solutions commonly used in the food industry. It appears that this novel disinfection system could represent an alternative to chlorine (sodium hypochlorite) disinfection, which is currently the most widespread method used by fresh-cut industries. Thus, EOW shows promise

Table 18.6 Application of electrolyzed water (EW) and acidic electrolyzed water (AcEW) in extending shelf life of fresh-cut fruits and vegetables

Conditions	Results	Author
Fresh-cut apple and cantaloupe (dip-inoculated with *E. coli O157:H7*)		
AcEW (pH 2.7), 68–70 mg L^{-1} free chlorine, 8 min	1 log CFU cm^{-2} reduction	Wang et al. 2008
Fresh-cut cabbage		
AcEW (pH 2.5-2.7), 20–40 mg kg^{-1} available chlorine	Reduced *E. coli* by approx. 1 log CFU g^{-1}	Achiwa et al. 2004
AcEW (pH 6.1), 20 mg L^{-1} available chlorine	Reduction of 1.5 log CFU g^{-1} for total aerobic bacteria and 1.3 log CFU g^{-1} for molds and yeasts	Koide et al. 2009
AcEW (pH 2.5–2.7), 20–40 mg kg^{-1} available chlorine	Effective treatment without producing trihalomethanes or causing abnormality in odor or taste, even when used on foods supplied directly to consumers	Achiwa et al. 2003
Fresh-cut leaves of romaine or iceberg lettuce (inoculated with *E. coli O157:H7*)		
AcEW (pH 2.6), 50 ppm free available chlorine	Reductions of less than 1 log CFU g^{-1}	Keskinen et al. 2009
Fresh-cut lettuce and fresh whole spinach leaves (inoculated with *E. coli O157:H7*, *Salmonella Typhimurium*, and *L. monocytogenes*)		
AcEW, alkaline EW water, and deionized water	Alkaline EW 3 min treatment reduced 3 tested pathogens	Park et al. 2008
Fresh-cut lettuce (inoculated with *L. monocytogenes*)		
AcEW-ice (20, 50, 100, and 200 ppm available chlorine)	AcEW-ice, prepared by freezing at −40 °C with 30, 70, 150, and 240 ppm chlorine gas, generated 70–240 ppm of Cl_2, reducing *L. monocytogenes* and *E. coli O157:H7* by 1.5 log CFU g^{-1}	Koseki et al. 2004
Fresh-cut lettuce leaves (inoculated with *L. monocytogenes* and *E. coli*)		
AcEW (45 ppm residual chlorine) compared to chlorinated water	Difference between bactericidal activity of AcEW and chlorinated water was not significant	Park et al. 2001
Fresh-cut cabbage and lettuce		
AcEW, 150 ppm NaOCl, tap water	Loss in quality of AcEW-treated cabbage and lettuce was equivalent to NaOCl and tap water treatment	Koseki and Itoh 2001
Fresh-cut lettuce and cabbage		
AcEW	Decrease at 1 °C, 5 °C, and 10 °C storage decreased microbial populations	Koseki and Itoh 2001
Fresh-cut cilantro		
AcEW, 24 % NaOCl, deionized water	NaOCl and deionized water were pumped into generator chamber; final concentration of sodium chloride solution passing through electrodes in AcEW generator chamber was 0.2 %; AcEW alone resulted in moderate control of aerobic bacterial growth during storage	Wang et al. 2004

(continued)

Table 18.6 (continued)

Conditions	Results	Author
Fresh-cut vegetables: carrot, spinach, bell pepper, Japanese radish, potato, and cucumber		
EW (pH 6.8), 20 ppm available chlorine	Effective as a disinfectant for tested fresh-cut vegetables without causing discoloration	Izumi 1999
Green onion and tomato (inoculated with *E. coli O157:H7*, *Salmonella typhimurium*, and *L. monocytogenes*)		
AcEW treatment 5, 10, 15, and 20 ml L^{-1} for 15 s, 30 s, 1 min, 3 min and 5 min	Reduced levels of cells to below detection limit (0.7 log CFU g^{-1}) within 3 min	Park et al. 2009
Fresh-cut salad products (cabbage, lettuce, carrot, red cabbage, paprika, onion, *wakame* seaweed, cucumber, red leaf lettuce, tomato, asparagus, corn, green pepper, onion, potato, tomato with tuna)		
AcEW (pH 2.5–2.7), available chlorine 20–40 mg kg^{-1}	Group A: tested commercial salads from supermarket – no significant bactericidal effect Group B: tested salads from restaurants – strong bactericidal effects	Achiwa et al. 2004
Fresh-cut mixed leafy greens (spinach and lettuce) (inoculated with *E. coli* O157:H7, *Salmonella*, and *L. monocytogenes*)		
AcEW (pH 2.1), 30–35 ppm free chlorine	Oxygen reduction potential 1,100 mV, 2.1–2.8 log CFU g^{-1} reduction	Stopforth et al. 2008
Fresh-cut salad: carrot, endive, iceberg lettuce, 'Four seasons' salad, corn salad		
NEW (pH 8.6), 50 ppm free chlorine	Reduction in amount of free chlorine used to disinfect fresh-cut product, with same microbial reduction effectiveness as sodium hypochlorite	Abadias et al. 2008
Fresh-cut spinach, lettuce (inoculated with *E. coli*, *Salmonella typhimurium*, *Staphylococcus aureus*, *L. monocytogenes*, and *Enterococcus faecalis*)		
NEW (pH 6.3), 1 % NaCl, 20, 50, 100, and 120 ppm total residual chlorine for 10 min	Resulted in 100 % inactivation of all 5 organisms (6.7 $\log_{10}$ CFU mL^{-1})	Guentzel et al. 2008

as an environmentally friendly broad-spectrum microbial decontamination agent. However, in terms of extending the shelf life of fresh-cut products, it is likely that further research will be needed due to the low power of microbial inactivation and scarce reportage on enzyme inactivation.

18.11 An Emerging Nonthermal Technology: Cold Plasma

Cold plasma is considered a relatively new decontamination technology in the field of food processing. Plasma is often referred to as the fourth state of matter after solid, liquid, and gas and is actually a mix of ionized gas molecules and free electrons. Cold plasma is electrically energized matter in a gaseous state, and it

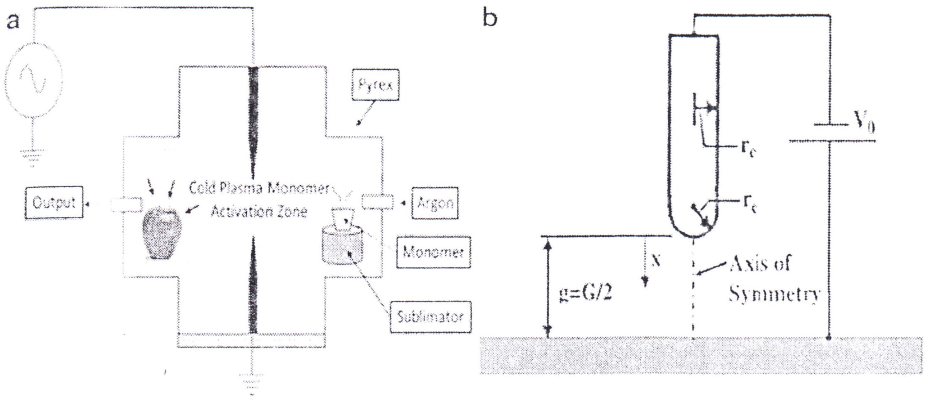

Fig. 18.1 (a) Schematic illustration of an experiment utilizing cold plasma to treat red delicious apples. (b) Simplified model used to approximate the on-axis electric field in Fig. 18.1. (a) Parameter r_c is the radius of curvature of the needle tip as described by Fernandez-Gutierrez et al. (Song et al. 2009)

can be generated by electrical discharge (Song et al. 2009). When a gas passes through plasma, the gas becomes excited, ionized, and full of dissociated electrons, leading to the formation of active species such as atomic oxygen, ozone, and free radicals (e.g., hydroxyl, superoxide, and nitrogen oxides). These reactive species have been shown to have antimicrobial activity (Critzer et al. 2007; Chunqi et al. 2009) by oxidation, although the exact mechanism of microbial cell inactivation is not fully understood (Fernandez-Gutierrez et al. 2010).

Formerly, stable glow discharge plasma could only be generated under vacuum or with gases such as helium and argon. However, researchers have now developed methods for electrically generating nonthermal gas plasma at ambient conditions, resulting in reduced costs and, more practically, offering a potentially new process for ensuring microbial safety and extending the shelf life of food products. Moreover, the relatively low discharged plasmas make their use suitable for heat-sensitive products (Kim et al. 2011).

For the calculation of the electric field intensity E of a needle, as illustrated in Fig. 18.1, the following equation may be used:

$$Ex(x) = E(x) = \frac{-2gVo}{ln\frac{(4g)}{r_c}\left[g(2x + r_c) - x^2\right]}. \tag{18.9}$$

To estimate the number of free electrons (as a function of distance from the negative needle point) associated with an avalanche initiated at the negative needle tip in a nonattaching (electropositive) gas such as argon, this can be written as

$$N(x) = N(0)exp\left[\int_0^x \alpha(E(x))dx\right], \tag{18.10}$$

Table 18.7 Studies on microbial inactivation of fruit and vegetables using cold plasma

Conditions	Results	Author
Mango and melon (cut fruit surface inoculated *Escherichia coli, Saccharomyces cerevisiae, Pantoea agglomerans,* and *Gluconacetobacter liquefaciens*)		
8 kV, 30 kHz	3 log reduction	Perni et al. 2008
Golden Delicious apple (inoculated *Salmonella Stanley* and *E. coli 0157:H7*)		
15 kV, 60 Hz	3.4–3.6 log reduction	Kim et al. 2011
Golden Delicious apple (inoculated with *Listeria innocua*)		
10 kV, 115–150 mA	0.39–1.1 log reduction	Niemira et al. 2005, cited in Niemira and Sites 2008
Seeds: tomato, wheat, bean, chick pea, soybean, barley, oat, rye, lentil, corn (inoculated with *Aspergillus paraciticus* 798. and *Penicillum* MS 1982)		
20 kV, 1 kHz	3 log reduction	Selcuk et al. 2008
Almond (inoculated with *E. coli*)		
30 kV, 2 kHz	5 log reduction	Deng et al. 2007
Peanut and pistachio (inoculated with *A. parasiticus* and aflatoxins)		
20 kV, 1 kHz with total applied power approximately 300 W	5 log reduction	Basaran et al. 2008
Apple, cantaloupe, and lettuce (inoculated with *E. coli* O157:H7, *Salmonellan* and *Listeria monocytogenes*)		
9 kV, 6 kHz	5 min treatment resulted in > 5 log reduction	Critzer et al. 2007
Lettuce (inoculated with *E. coli* ATCC 11775)		
5.7 kV RMS in Argon, 0,5;3.0 and 5.0 min	1.2 log reduction	Bermudez-Aguirre et al. 2011

where $N(x)$ and $N(0)$ represent the numbers of free electrons at locations x and $x = 0$, respectively, and α is Townsend's first ionization coefficient given by

$$\frac{\alpha}{p} = Aexp\left(-\frac{C}{E/p}\right) \tag{18.11}$$

with $A = 1{,}200\ \mathrm{m}^{-1} \cdot \mathrm{torr}^{-1}$ and $C = 20{,}000\ \mathrm{V} \cdot \mathrm{m}^{-1} \cdot \mathrm{torr}^{-1}$, where p is the pressure in torr, and the E/p range for A and C is $C/2 < (E/p) < 3C$ (Fernandez-Gutierrez et al. 2010).

The term cold plasma is a relative term that, in the context of food processing, refers to the capability to generate and apply the plasma nonthermally (Niemira and Sites 2008). This technology is experiencing a heightened interest and research focus by both plasma science researchers and food scientists. Comprehensive review articles and excellent book chapters about the utilization of cold plasma in food processing are available (Misra et al. 2011; Knorr et al. 2011); unfortunately, information about the application of cold plasma on fruit and vegetable products is largely lacking. Table 18.7 summarizes several studies on the utilization of cold plasma with fruit and vegetable products; however, for fresh-cut products, the literature remains scarce.

The advantage of cold plasma in food application is that it allows for microbial inactivation at a low temperature by generating free radicals in the plasma environment, provides uniform treatment, and diffuses into complicated structures with a relatively short processing time. In addition, plasma does not require chemicals, and hence does not leave toxic residues, and it is harmless for operators (Selcuk et al. 2008).

Based on the studies summarized in Table 18.7, cold plasma has a promising future application in the extension of the shelf life of fresh-cut fruits and vegetables. This extended shelf life is attributed to the microbial disinfection provided by this technology at low temperatures on food surfaces by the generation of free radicals that inactivate microorganisms, resulting in food products that are free of any residues and retain the freshlike characteristics of fresh-cut products.

18.12 Final Remarks

Current techniques used by the fresh-cut industry have improved the overall quality of products; however, extending shelf life while guaranteeing safety is still an issue of great concern. Development of novel approaches to assuring the quality and safety of fresh-cut produce has led to the utilization of nonthermal technologies. The benefits of using these technologies lie in the minimal adverse effects on product quality since these decontamination processes do not produce heat. The issue of shelf-life extension of fresh-cut produce using nonthermal technology cannot be separated from and goes hand in hand with safety. The longer shelf life of fresh-cut products in this case is achieved by reducing and minimizing microbial contamination.

Research focus on the utilization of nonthermal emerging technologies has mainly been on extending shelf life and ensuring the safety of products, which has led to several promising nonthermal technologies for later advanced commercial application, though some are commercially available today. The potential of commercial nonthermal technologies in prolonging fresh-cut-produce shelf life is summarized in Table 18.8.

To sum up, most studies have reported that nonthermal processing is a promising means of extending the shelf life, enhancing the safety, and maintaining the freshlike characteristics of fresh-cut fruits and vegetables. On the other hand, due to the extensive current studies on microbial inactivation using nonthermal technologies, as noted in Table 18.8, most exist at the laboratory level with application to certain bacteria and several fresh-cut products. There is relatively limited explanation on the scale-up of these technologies, and available comprehensive data on microbial decontamination using nonthermal processes in the fresh-cut industry are scarce. Therefore, to make commercial adoption easier for the

Table 18.8 Application of shelf-life extension of fresh-cut products using nonthermal technologies

Type of nonthermal technology	Research on fresh-cut fruits and vegetables	Commercial potential
High-pressure processing	Proven to extend shelf life without compromising freshlike quality; adequate microbial decontamination at appropriate levels of pressure for most fresh-cut fruits and vegetables	++
Pulsed electric fields	Several drawbacks noted; this technology is suitable for liquid foods and can assist in drying fresh-cut foods; for all practical purposes as of today, this technology is not appropriate for fresh-cut products	−
Irradiation	Low-dose irradiation has proven effective in extending shelf life and quality	+++
Ozone	Has proven to be an effective decontamination agent as compared to chlorine; environmentally friendly disinfectant	++
UV radiation	Low-dose UV radiation has proven effective for microbial decontamination in combination with other preservation methods	+
Ultrasound	Has proven to have a microbicidal effect in combination with other preservation methods	+
Electrolyzed water	New system and a decontamination agent; could be a replacement for sodium hypochlorite; environmental friendly disinfectant	+
Cold plasma	Microbial inactivation by generating free radicals at low temperature, resulting in food products free of all residue	+

fresh-cut fruit and vegetable industry, future work focusing on the extensive scale-up and guidelines describing potential nonthermal processes for commercial use to extend the shelf life of fresh-cut products will definitely be required.

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