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

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Abstract

The fresh-cut fruit and vegetable market has grown rapidly in recent years with justifiable expectations of continuous growth. On the other hand, such products are still under study in order to improve the quality, safety and, in particular, the shelf life of the products to fulfill consumers' expectations. Numerous applications of recent science and technologies have been conducted in an attempt to prolong the shelf life of these products. Extended shelf life in foods has traditionally been linked with thermal processing by inactivating food spoilage and pathogenic microorganisms. Heat treatment, however, leads to destruction of freshness and nutrient losses. One of the promising approaches being considered is to utilize nonthermal technologies that, to some extent, achieve fresh-like quality and a safe product with high nutritional value. This chapter reviews updated contributions regarding the minimal processing of plant food products in order to maintain and achieve freshness and longer shelf life. Special attention is given to the newest trends in nonthermal technologies for fresh-cut fruits and vegetables.

Key words: *Fresh-cut fruits and vegetables, minimally processed products, nonthermal technologies*

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 fruits and vegetables market has grown rapidly in recent decades. In 2003 the fresh-cut industry represented 50% of fresh produce sales [Zaborowski, D., 2003], and in 2007 retail sales accounted of \$998.25 billion [Cook, R., 2007] in the United States. Meanwhile, in Germany the turnover of fresh food industries was around €52 billion in 2000 [Entrup, M. L., 2005], with justifiable expectations of continued increase due to the popularity of fresh food as a convenient and healthy food choice [Artés, F.; Allende, A., 2005; Rico, D. et al. 2007].

The International Fresh-cut Produce Association (IFPA) defines fresh-cut products as fruits or vegetables that have been trimmed and/or peeled, and/or cut, into a 100% usable product that is bagged or pre-packaged 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, retaining nutrition and sensory quality are also required, while providing extended shelf life [González-Aguilar, G. A. et al, 2004].

Interestingly, one of the foremost challenging problems in the commercialization of these products is usually their short shelf life and declining quality after processing [Du, J. et al, 2009; Jacxsens, L. et al, 1999]. The shelf life of fresh-cut fruit and vegetables varies from 3 to 7 days and depends on the products; however, longer shelf life is better to make safe distribution feasible. Shelf life is the time a product can retain its quality under standardized storage conditions before its attributes drop below the acceptance limit [Tijskens, L. M. M., 2000]. It is broadly believed that the processing of fruits and vegetables promotes faster physiological deterioration, biochemical changes and microbial degradation of the product, even when minimal processing operations are applied [O'Beirne, D.; Francis, G. A., 2003]. These changes, such as degradation of color, texture and flavor, will reduce the shelf life of these products compared to unprocessed products [Watada, A. E. et al, 1990].

Furthermore, providing information about the safety of these products is still an issue of heightened concern to consumers. Meanwhile, fresh-cut fruits and vegetables are highly perishable since a large proportion of those damaged have exposed surface areas without epidermis, i.e., the outer protective layer of the tissue [Sandhya, 2010; Watada, A. E., 1999]. Therefore, the fresh-cut produce industry is challenged with potential outbreaks of illness that could be associated with microbial growth during the extended shelf life of these products [Alzamora, S. M.; Guerrero, S., 2003]. This threat is due to the fact that these products provide a viable medium for the growth of microorganisms.

In response to these challenges, many efforts using recent science and technologies have been conducted in an attempt to prolong the shelf life of these products, as well as to improve their quality and safety. Extended shelf life of foods has traditionally been linked with thermal processing. Heat treatment, however, leads to destruction of freshness and nutrient losses. As a consequence it is imperative that new preservation methods be found that cause only minimal adverse changes in foods, with limited use (or none at all) of additives, while offering desirable benefits derived from an increased shelf life [Camelo, A. L. et al, 2003]. One approach that promises to increase the shelf life of fresh-cut products is to use nonthermal technologies, which, to some extent, achieve a fresh-like quality and safe product and retain high nutritional value. The emergence of novel nonthermal technologies which are often regarded as *invisible preservation*, allows the production of high quality products with improvements in shelf life and fresh-like characteristics. The present review summarizes recent contributions reported on minimal processing of plant food products using nonthermal technologies to maintain freshness and achieve longer shelf life.

Physiological effects of processing operation on fresh-cut plant products

Fresh-cut fruits and vegetables are products partially prepared so that no additional preparation is necessary for their use. Fresh-cut products have also been referred to as *lightly processed*, *minimally processed*, *fresh processed*, *partially processed* or *pre-prepared* products [Garcia, E.; Barrett, D. M., 2005]. Generally, it is unavoidable that the overall quality is impaired during processing and storage. The increasing demand for convenient fresh-cut products has a detrimental effect on product quality. Physiologically, the operations of preparation damage the integrity of the cells, promoting contact between enzymes and substrates, the entry of microorganisms, and creation of stress conditions [Fonseca, S. C. et al, 1999]. The consequences of wounding are: (1) increase in respiration rate; (2) production of ethylene; (3) oxidative browning; (4) water loss; and (5) degradation of membrane lipids [Brecht, 1995, cited in Fonseca, S. C. et al, 1999]. Therefore, fresh-cut fruits and vegetables

tend to be more perishable than the commodity from which they were prepared [Kader, A. A., 2002].

Cutting is the main factor responsible for the deterioration of these products during storage which, as a consequence, is more rapid than in unprocessed (whole) products [Degl'Innocenti, E. et al, 2007]. Damaged plant tissues exhibit an increased respiratory rate [Fonseca, S. C. et al, 2002]. Treatment applied after, or before, wounding can affect the respiration rate [Del Nobile, M. A. et al, 2006]. Therefore, cutting induces deteriorative changes associated with plant tissue senescence and a consequential decrease in shelf life relative to unprocessed produce.

It is also well established that a faster rate of enzymatic browning by cutting is considered to be one of the major limitation factors detrimental to many fresh-cut products, such as apples, bananas, potatoes and lotus root, since browning is easily detected by consumers, with evident consequences on marketing [Degl'Innocenti, E. et al, 2007; Luo, Y.; Barbosa-Cánovas, G. V., 1996]. Polyphenoloxidase (PPO, EC1.14.18.1) activity is known to be the main cause involved in browning [Walker, J. R. L.; Ferrar, P. H., 1998].

Another important enzyme influenced by cutting is lipoxidase, which catalyzes the peroxidation reaction, thus causing the formation of numerous bad smelling aldehydes and ketones [Varoquaux, P.; Wiley, R., 1994]. Furthermore, a faster rate of softening of tissue results from an increase in ethylene production during this fresh-cut processing, due to the fact that ethylene contributes to the biosynthesis of enzymes in fruit maturation, and is partially responsible for the physiological changes in sliced fruit.

These physiological changes may be accompanied by flavor loss, cut surface discoloration, color loss, decay, increased rate of vitamin loss, rapid softening, shrinkage and a shorter storage life. Increased water activity and mixing of intracellular and intercellular enzymes and substrates may also contribute to flavor and texture change/loss during and after processing [Sandhya, 2010]. By understanding the physiological changing mechanisms of fresh-cut processing and controlling factors that have a detrimental effect on quality, good quality fresh-cut products with sufficient shelf life can be obtained.

Nonthermal technologies

The term *nonthermal processing* is often used to designate technologies that are effective at ambient or sublethal temperatures [Pereira, R. N.; Vicente, A. A., 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, B.; Knorr, D., 1992]. High capital investment on 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, J. et al, 1999]. Therefore, nonthermal technologies may play an important role in producing more convenient fresh-like products, as well as 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.

High Pressure Processing (HPP)

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

$$\Delta G = G^{(\text{products})} - G^{(\text{reactants})} \quad \text{equation 1}$$

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

$$dG = -SdT + VdP + \sum \mu_i dn_i \quad \text{equation 2}$$

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 compound [Welti-Chanes, J. et al., 2005]. The above equation is the basic principle equation of Gibbs, while the next equation correlates the influence of pressure on G with volume:

$$V = \left[\frac{\partial G}{\partial P} \right]_{T, n_i} \quad \text{equation 3}$$

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

It has been reported that there are some problems that may arise associated with the use of HPP on certain plant material systems, as 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 fully suitable for all plant products [Palou, E. et al., 2000].

On the other hand, Torres and Velazquez [2005] identified that fresh-cut products represent one of many opportunities in which HPP has a clear competitive advantage. Nishin Oil Mills, a Japanese food manufacturer, has produced non-tropical fruits using high pressure processing at pressures 50-200 MPa ("freezing" temperature, -18°C) (Campden New Technology bulletin no. 14; cited in Ohlsson, T.; Bengtsson, N. (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. There are several companies (Avure: <http://www.nchyperbaric.com> and NC Hyperbaric: <http://www.avure.com>) manufacturing HPP equipment that 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 1.

Table 1. Application of HPP on fresh-cut fruits and vegetables

Conditions	Results	Author
Fresh-cut pineapple		
200, 270 and 340 MPa; -4, 21 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, G. et al, 1994
270 MPa for 9000 s	Inoculated with 10^{4-5} CFU g ⁻¹ <i>Saccharomyces cerevisiae</i> , packed in heat-sealed polyethylene pouches and subjected to static and step pulses pressure. Step pulsed pressure resulted in higher destruction of microorganisms tested	Alemán, G. 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, W.; An, G. J., 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, W.; Zhang, H. H., 2009
Fresh-cut Chinese yam		
600 MPa for 10 min	Effectively prevented browning and microbial growth when stored at 4°C for 9 days	An, G. J.; Li, B., 2007
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, N. et al, 2010
Packaged fresh-cut melon		
600 MPa for 10 min	Enhancement of β -carotene and minimal loss of sensorial properties and health-promoting phytochemicals	Wolbang, C. M., 2008

In terms of microbial inactivation using HPP treatment on fresh-cut plant products, Alemán et al. [Alemán, G. et al, 1994] reported application of HPP on fresh-cut pineapple in combination with pressure of only 270 MPa for 15 min, resulting in more than 2 decimal reductions at a temperature of 38°C. Meanwhile, Alemán et al. (1998) reported that step pulsed pressure could reduce the number of yeast and bacteria with 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) mentioned that spore inactivation is a primary challenge in HPP application; today, the challenge has been answered. Bermudez-Aguirre and Barbosa-Cánovas (2011) emphasized

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

As shown in Table 1, HPP has several advantages as a treatment for fresh-cut fruits and vegetables. HPP allows ‘in-packaged fresh-cut fruit and vegetable processes’ that reduce the microbial load and extend the product’s shelf life. Wolbang et al. (2008) investigated the effect of HPP on the nutritional content of packaged cut melon. It was proven that HPP enhanced not only microbial inactivation, but also the level of health-promoting phytochemicals, with a minimal loss of sensorial qualities. Recent findings by Perera, N. et al (2010) using HPP on fresh-cut apple cubes 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 about 40% PPO in Granny Smith apples. This means that HPP treatment has the potential to prevent browning of fresh-cut fruits. This result is in agreement with the finding by An and Li (2007). They 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 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, S.; Zhang, Q., 2005]. Several enzymes which are partially responsible for oxidative degradation reactions in fresh-cut fruits and vegetables such as polyphenoloxidase (PPO), lipoxygenase (LOX), pectinmethylesterase (PME) that have been inhibited by HPP treatment [Garcia-Viguera, C.; Bridle, P., 1999; Garzon, G. A.; Wrolstad, R. E., 2002]. However, during HPP application, it should be pointed out that the residual potent activity and/or the activation of endogenous enzymes depend on the pressure, temperature and time at which HPP is applied [Del Pozo-Insfran, D. 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, Y. H.; Nip, W., 2004].

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

Pulsed Electric Fields (PEF)

PEF has been used as an alternative to heat pasteurization for processing real food systems, including fruit and vegetable tissues [Knorr, D.; Angersbach, A., 1998]. A number of experiments have been conducted to study the mechanism and safety of microbial inactivation under PEF treatment [Buchanan, R. L. et al, 1998; Jin, Z. T. et al, 2001; Raso, J. et al, 1998]. Membrane permeability (i.e., damage in cell membranes) has been proposed as the causative factor behind microbial inactivation [Harrison, S. L. et al, 2001]. Another approach was reported by Harrison et al. [Harrison, S. L. et al, 1997] in which the 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, J. et al, 2001]. Some studies have used fruits and vegetables as media for inactivation of enzymes. Changes in enzyme conformational structure specifically have been reported by several authors [Ho, S. Y. et al, 1997; Vega-Mercado, H. et al, 1995]. Further, enzymes have different sensitivities to PEF treatments, and many factors influence PEF enzymatic inactivation [Yeom, H. W.; Zhang, Q. H., 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 electro-permeabilization and loss of turgor [Fincan, M.; Dejmek, P., 2003], can be utilized to reduce the energy required for cutting of plant material as well as to enhance juice extraction. Therefore, PEF technology is mainly intended for preservation of pumpable fluids [Hui, Y. H.; Nip, W., 2004, Qin, B.-L. et al, 1996], predominantly fruit and vegetable juices [Min, S. et al, 2003, Heinz, V. et al, 2003]. In fact, the adoption of PEF for commercial nonthermal pasteurization of fruit juices was first implemented by Genesis Juices, Oregon, USA [Clark, J., 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, G. V. et al, 997]. 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.

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, M.; Polat, M., 2005]. Irradiation literally means exposure to irradiation [Grandison, A. S., 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, B. A.; Deschenes, L., 2005]. Irradiation is a nonthermal technology or *cold process* due to only few degrees increase in foods 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 food-borne pathogens and natural contaminants from fresh fruits and vegetables [Thayer, D. W.; Rajkowski, K. T., 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, R., 2001]. Irradiation affects microorganisms such as bacteria, yeasts, and molds by causing lesions in the genetic material of cells, effectively preventing the cells from carrying out the biological processes necessary for continued cell existence [Rahman, M. S., 1999]. Irradiation can reduce the incidence of pathogenic microorganisms associated with fresh-cut products, without changing the minimally processed character of the products [Farkas, J. et al, 1999]. Thus, irradiation is one of the potential effective technologies that can inactivate food-borne pathogens in fresh-cut fruits and vegetables.

The FDA has approved the use of irradiation on wheat and potatoes since 1963; on spices, pork, fruits and vegetables in the 1980s; poultry in the early 1990s; and red meats in (beef, veal, lamb) [Majchrowicz, A., 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, M. et al, 2003; Sharma, A., 2004].

Table 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 could be a suitable method for extending shelf life while ensuring product safety by inactivation of microorganisms on fresh-cut fruits and vegetables [Buchanan, R. L. et al, 1998; Hagenmaier, R. D.; Baker, R. A., 1997].

Table 2. The application of low-dose irradiation for extending shelf life of fresh-cut fruits and vegetables

Dosage	Results	Autor
Fresh-cut lettuce		
1.0 kGy	Number of aerobic mesophyllic bacteria was reduced by 2.35 logs; sensory quality was maintained best during storage for 8 days at 4°C	Zhang, L. et al, 2006
0.5 and 1.0 kGy	Similar firmness and vitamin C and antioxidant contents as the controls after 14 and 21 days of storage	Fan, X. et al, 2003
0.19 kGy	8 days after irradiation microbial population was much lower compared to non-irradiated	Hagenmaier, R. D.; Baker, R. A., 1997
0.15, 0.38, or 0.55 kGy	5-log reduction in <i>E. coli</i> 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, D. M., 2002
1.0 kGy	Eliminated bacterial contamination from lettuce sample without any sensorial quality defects	Kim, J.-H., 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, J., 2004
0.3 to 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, A. M.; Foley, D. M., 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, X., 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 non-irradiated samples	Castell-Perez, E., 2004
up to 1.5 kGy	Irradiated samples resulted in a much higher reduction, 3 log TPC number; shelf life was extended up to 11 days of storage	Boynton, B. B. et al, 2005
0.5 and 1.0 kGy	Color and texture remained stable after 20 days storage; low-dose irradiation may increase shelf life while maintaining high product quality	Boynton, B. B., 2004
0.5 kGy	Low microbial load similar to that of cubes prepared from hot-water-treated fruit	Fan, X. et al, 2006
0.7 and 1.4 kGy	Irradiation reduced total aerobic microbial counts with increasing doses	Palekar, M. P. 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, S., 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, J. M., 2002
Fresh-cut apple		
up to 5.0 kGy	Threshold for maintaining firmness of sliced apples was 0.34 kGy	Gunes, G. et al, 2001
0.5 and 1.0 kGy	Enhanced microbial food safety while maintaining quality of fresh-cut apple slices	Fan, X. et al, 2005
1.6 kGy	Did not significantly affect color, soluble solid content, titratable acidity, or apple aroma intensity	Fan, X. 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, G. 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, Z. 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, A. 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, L. 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 storage	Kim, H. J. et al, 2005
1.0 kGy	Reduced aerobic plate counts, yeasts and molds, and psychrotrophic counts by 3-5 logs CFU g ⁻¹ without negatively affecting quality (14 days storage)	Butris, S. et al, 2003
Fresh-cut tomato		
0.7 and 0.95 kGy	Reduction of 1.8 and 2.2 log ₁₀ CFU g ⁻¹ on tomatoes inoculated with <i>Salmonella</i> for 0.7 and 0.95 kGy	Schmidt, H. M., 2004
up to 0.9 kGy	D-value ranged from 0.26 to 0.39 kGy, indicating that a 5 log ₁₀ CFU g ⁻¹ reduction in <i>Salmonella</i> spp. in diced tomatoes would require a dose of 1.3-1.95 kGy	Prakash, A. 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, S. D. 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, H.-J. et al., 2005
Fresh-cut broccoli heads		
1.0, 2.0, and 3.0 kGy	Treatment up to 3 kGy maintains overall quality of fresh broccoli	Gomes, C. et al., 2008
Fresh-cut mint (inoculated with <i>E.coli</i> O157:H7, <i>Salmonella</i> and MS2 bacteriophage)		
up to 2.0 kGy	Population decreased up to 5.8 log CFU g ⁻¹ , and 1.0 to 2.0 kGy appears promising as a method for improving microbiological quality of fresh mint without compromising visual and color attributes	Hsu, W.-Y. et al., 2010
Fresh-cut carrot		
2.0 kGy	2- to 4-fold increase in shelf life at refrigeration temperature	Kamat, A. S. et al., 2005
2.0 kGy	Prevented losses of orange color and carotenes; sensory analysis demonstrated preferences for irradiated vegetables	Chervin, C.; Boisseau, P., 1994
2.0 kGy	Significant reduction in respiration by 50% and ethylene production by 80%	Chervin, C. et al., 1992
0.5 kGy	Shredded carrots treated with irradiation had a mean microbial population of 1300 CFU g ⁻¹ at expiration date (9 days after irradiation) compared to 87,000 CFU g ⁻¹ for non-irradiated, chlorinated controls	Hagenmaier, R. D.; Baker, R. A., 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 food borne pathogens without impairing quality, at following doses: 1.5 kGy for celery (14 days storage); 2 kGy for lettuce, green beans, apples, pears (15 days storage); 3 kGy for cucumbers, mixed vegetables salad, mixed peas with diced carrots (15 days storage); and 4 kGy for carrots (21 days storage)	Hammad, A. A. et al., 2006
Fresh-cut fruits (pineapple, jackfruit, mixed fruits) and vegetables (onion and cucumber)		
0.0 to 3.0 kGy	Low-dose irradiation eliminated or reduced risk of food borne pathogens and did not affect the color (lightness, redness and greenness) of minimally processed onion and cucumber	Faridah, M. S. 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, N. et al., 2006
Fresh-cut coriander, lettuce, mint, parsley, turnip, watercress, melon and watermelon inoculated with <i>E. coli</i> O157:H7 and <i>L. innocua</i>		

up to 1.0 kGy	No important differences were found overall in sensorial and physico-chemical properties after irradiation up to 1 kGy	Trigo, M. et al., 2006
Fresh-cut (shredded) carrot, mixed salad samples (radicchio and butterhead lettuce), red leaf lettuce, green lettuce and soybean sprouts (inoculated with <i>L. monocytogenes</i>, <i>E. coli</i> 0157:H7 and <i>Salmonella</i>)		
1.0 to 1.5 kGy	Inactivation of pathogens, no effect on sensory attributes during storage	Basbayraktar, V. et al., 2006
Fresh-cut ready-to-use vegetables: cucumber, blanched and seasoned spinach (inoculated with <i>Salmonella typhimurium</i>, <i>E. coli</i>, <i>Staphylococcus aureus</i>, and <i>L. ivanovii</i>)		
up to 3.0 kGy	Low-dose irradiation (3 kGy or less) can improve microbial safety of ready-to-use vegetables	Young Lee, N. et al., 2006
Fresh-cut cauliflower		
1.5 kGy	Treatment maintained quality of fresh-cut cauliflower	Nunes, T. C. F. et al., 2009
Fresh-cut red beet		
1.0 or 2.0 kGy	Pigments seemed to overcome irradiation dose of 1 kGy	Latorre, M. E. 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 five days storage at 10°C	Hanotel, L. et al., 1995

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 non-irradiated 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 micro-porous bags, resulting in limited respiration increase due to wounding and reduced ethylene production, and increasing the shelf life of the product [Chervin, C. 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 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 destruction of the quality of fresh-cut plant products have been observed. As shown in Table 2, irradiation doses should be kept as low as possible to achieve the safe quality of the product and extend shelf life, without decreasing the organoleptic quality of fresh-cut products. Grandison (2006) mentioned 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, M. H. F. 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 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

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 gaining more interest [Guzel-Seydim, Z. B. et al., 2004]. There are a number of reviews about the utilization of ozone technology in food processing [Kim, J.-G. et al., 2003, Khader, M. A. et al., 2001] and in particular, fresh-cut processing [Strickland, W. et al., 2010]. Ozone, with its high oxidizing power, is considered to be a strong antimicrobial agent with high reactivity and thus it is applicable in ensuring the microbial safety of raw produce [Khader, M. A. et al., 2001]. Due to its instability, ozone does not produce persistent disinfection residuals [Kim, J.-G. et al., 2003]. The spontaneous auto-decomposition to a non-toxic product with 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, K. et al., 2000] and was deemed GRAS (Generally Recognized As Safe) in July 1997 by an independent panel of scientists [Majchrowicz, A., 1999]. Fruits and vegetables have the advantage of having smooth surfaces with low ozone demand [Khader, M. A. 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, F.; Allende, A., 2005] and numerous researchers have focused as well on ozone application to other fresh-cut products (Table 3).

As shown in Table 4, extending shelf life and preserving the fresh-like quality of fresh-cut products can be achieved by ozone treatment, particularly in the form of aqueous ozone.

Table 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 <i>L. monocytogenes</i> on green leaf lettuce, sensory quality during cold storage	Ölmez, H.; Akbas, M. Y., 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, S. 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 to 4 log unit in reductions of microorganisms, similar to results achieved with 100 mg L^{-1} chlorinated water	Kim, B. S., 2006
5 ppm O_{3A} for 5 min	Reduction of microbial count by 1.8 log units	Selma, M. V., 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, M. Y.; Ölmez, H., 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 sensorial quality and browning control with no detrimental reduction in antioxidant constituents	Beltran, D. et al., 2005
Aqueous O_3 (3,	Bacterial reduction of 1.4 log CFU g ⁻¹ up to 5 ppm aqueous O_3	Koseki, S.;

5, and 10 ppm)		Isobe, S., 2006
1, 3, and 5 ppm O _{3A} for 0.5, 1, 3, or 5 min	1.09 and 0.94 log reductions of <i>E. coli</i> O157:H7 and <i>L. monocytogenes</i> , respectively	Yuk, H.-G. et al., 2006
1 mg L ⁻¹ O _{3A} at 18-20°C	Enzymatic activity decreased significantly	Rico, D. et al., 2006
O _{3A} at 4°C for 6 days	An industrial trial: O ₃ generator was integrated into a commercial lettuce-washing facility. Quality of lettuce during storage was unaffected; however, only limited destruction existed in microbial population	Hassenberg, K. et al., 2007
Fresh-cut celery		
O _{3A} at different doses	0.18 ppm O _{3A} dipp resulted in the highest reduction of the microbial population	Zhang, L. 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, H. et al., 2004
Fresh-cut cantaloupe		
10000 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; while the combination of hot water and O _{3G} was most 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	Selma, M. V. et al, 2008
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, A. C. et al., 2010
10000 ppm O _{3G} for 30 min under vacuum	Reduction and spoilage of fresh and fresh-cut melon	Selma, M. V. 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, M. V. 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, H., 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, B. K.; Kim, J. G., 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 did not cause any damage or off-flavor in sliced or whole tomatoes	Aguayo, E. et al., 2006

Fresh-cut green asparagus		
1 mg L ⁻¹ O _{3A}	Enzyme activity was inhibited	An, J., 2007
Fresh-cut baby leaf <i>Brassica</i> species (salad rocket, wild rocket, mizuna and watercress) stored at 1, 4, 8 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, while heat shock treatment was ineffective.	Martínez-Sánchez, A., 2008
Fresh-cut green bean and bell pepper		
2 ppm O _{3A}	Peroxidase inactivation, while color of vegetables was not affected	Elisabete M.C.; Joana, F., 2006

Dissolved ozone in water is a thermodynamic ideal condition, as expressed in the following equation:

$$Cs = \beta M \times P\gamma \quad \text{equation 10}$$

where Cs is saturation concentration, kg O₃ 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 γ 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:

$$Sr = \frac{\text{mg L}^{-1} \text{ O}_3 \text{ in water}}{\text{mg L}^{-1} \text{ in the gas phase}} \quad \text{equation 11}$$

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, K. L. 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 3, ozone was effective in eliminating inoculated microorganisms and extending shelf life, for example, fresh-cut lettuce inoculated by *L. monocytogenes* [Ölmez, H.; Akbas, M. Y., 2009] and *E. coli* O157:H7, *Salmonella enterica* serovar Typhimurium, *L. monocytogenes* and *Staphylococcus aureus* [Kim, B. S. et al, 2006]. A low level of ozone (2-3 ppm) for short exposure (2-5 min) was found to be an optimum processing condition for disinfection of fresh-cut lettuce in terms of reducing microbial load and maintaining sensory quality. Furthermore, Ölmez and Akbas (2009) reported that ozone treatment was found to be more effective than chlorine and organic acid treatments in maintaining sensory quality.

Kim et al. (1999) concluded that ozone is more efficient at lower concentrations and shorter treatment times than more standard sanitizers, including chlorine. Singh et al. (2002) reported that gaseous treatments of ozone were more effective than aqueous ozone in reducing *E. coli* O157:H7 on lettuce. Similar results were also reported by Bialka and Demirci (2007) in which reductions of *E. coli* O157:H7 and *Salmonella* were achieved on blueberries treated with gaseous ozone, among other treatments, and by Akbas and Ozdemir (2008) who found that a

decreasing number of *E. coli* and *Bacillus cereus* cells treated with gaseous ozone were achieved at low concentrations. Moreover, Klockow and Keener (2009) reported that ozone has the 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 used successfully applied since 2000 by Strickland Produce, Inc. [Strickland, W. et al., 2010]. Significant improvements in product quality, plus savings in water and labor, were achieved by the company with recovery of their investment in ozonation in less than two 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.

Ultraviolet (UV)

Excellent reviews about the benefits and adequacy of UV light (UV) processing in food applications have been published by several authors [Guerrero-Beltrán, J. A.; Barbosa-Cánovas, G. V., 2004]. Book chapters on ultraviolet processing of food are also available [Lopez-Malo, A.; Palou, E., 2005]. Bintsis et al. (2000) mentioned that some companies employ the use of 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. Thereby, this technology has been more applied on the surface of fresh-cut of fruit and vegetables than in liquid plant products [Bermudez-Aguirre, D.; Barbosa-Cánovas, G. V., 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, C. E.; Balasubramanian, V. M., 1999]. The effectiveness of microbial disinfection with UV light in extending the shelf life of fresh-cut products depends on several factors: product profile, wavelength, transmissivity of the product, geometric configuration of the reactor, and radiation path length [Hui, Y. H.; Nip, W., 2004]. High UV doses may promote damage to the treated tissue [Rico, D. et al., 2007], and in certain plants UV can easily cause off-flavors [Ohlsson, T.; Bengtsson, N., 2002].

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

$$I = I_0 \cdot e^{-kd} \quad \text{equation 12}$$

where I is the attenuated intensity, I_0 is the incident monochromatic UV intensity, and d is the depth reached by the UV light [Guerrero-Beltrán, J. A.; Barbosa-Cánovas, G. V., 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 following equation:

$$\log \frac{N}{N_0} = -kD \quad \text{equation 13}$$

where N_0 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, J. C. et al., 1985]. Another mathematical model has been described as follows:

$$\ln \frac{N}{N_0} = -kIt \quad \text{equation 14}$$

where N is the number of survival microorganisms after UV radiation, N_0 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, R. A. et al., 1987].

The application of ultraviolet in extending shelf life of fresh-cut vegetables has generated numerous studies, as summarized in Table 4 describing the effects of ultraviolet 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 could improve the shelf life and quality of fresh-cut cantaloupe melon. Application of low-dose UV has been shown to be effective against common foodborne pathogens [Sastry, S. K. 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.

Table 4. Extending shelf life of fresh-cut fruits and vegetables products using ultraviolet 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, but lower microbial count compared to untreated samples	Gómez, P. L. 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 the interior of the tissue	Manzocco, L. et al., 2009
Fresh-cut Tommy Atkins mango		
250 to 280 nm UV for 10 min	Improvement the total antioxidant capacity of fresh-cut mango	Gonzalez-Aguilar, G. A. et al., 2007
Fresh-cut baby spinach leaves		
Double-sided UV (2.4 to 24 kJ m^{-2})	At low doses, UV was effective in reducing initial psychrotrophic and <i>Enterobacteria</i> counts and kept <i>L. monocytogenes</i> at low levels during storage without affecting sensory quality	Escalona, V. H. 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 and overall visual quality	Fonseca, J. M.; Rushing, J. W., 2006
1.6, 2.8, 4.8 and 7.2 kJ m^{-2}	No significant effect on vitamin C content, while catalase activity and total polyphenols content declined	Artés-Hernández, F.

	considerably throughout storage	et al, 2010
Fresh-cut tropical fruits: honey pineapple, banana <i>pisang mas</i>, and guava		
2.1 J m ⁻² for 10, 20, and 30 min	Increase of total phenol and flavonoids, but a decrease in vitamin C	Alothman, M. et al., 2009
Fresh-cut cantaloupe		
UV (254 nm) for 15 and 60 min	Increase concentrations of terpenoids in cantaloupe tissue	Beaulieu, J. C., 2007
Fresh-cut (tissue slices) zucchini squash		
UV (250 to 280 nm) for 1, 10 and 20 min	Delaying senescence and deterioration in tissues, reducing the microbial population and improving storage quality	Erkan, M. 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, F. 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, M. et al., 2008
Fresh-cut tomato		
3.2 to 19.2 kJ m ⁻²	Reduction in development of microbial populations, increase phenolic content, and delayed degradation of vitamin C after 7 days of storage at 4-6°C	Kim, H. J. et al., 2008
Fresh-cut pineapple		
UV for 15 min, 1-2 cm ² slices	UV Fotodyne Model 3-3000 Transilluminator (Fotodyne Inc., Hartland, Wis., U.S.A.). UV-induction of phytoalexin compounds in pineapple; potential use of UV to elicit the natural defense mechanisms of fresh-cut fruits	Lamikanra, O.; Richard, O. A., 2004

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.

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 foods [Piyasena, P. et al., 2003]. Ultrasound consists of “elastics waves” with frequencies that are above the threshold of human hearing ($\cong 20$ kHz) [Mulet, A. et al., 2002].

The bacterial inactivation effect of ultrasound has long been observed (Harvey and Loomis, 1929, cited in Feng, H.; Yang, W., (2006)). The mechanical effects of power ultrasonics are mainly attributed to cavitation, the forces of which have a dramatic effect on biological systems [Mason, T. J.; Paniwnyk, L., 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, P.; Tauscher, B., 2002].

Table 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, J. H. et al., 2009
Fresh whole spinach leaves		
21.2 kHz	Significant reduction of <i>E. coli</i> cells on spinach in all treatments by 0.7-1.1 log compared to washing with a sanitizer alone	Zhou, B., 2009
Fresh-cut apple and lettuce (inoculated with <i>Salmonella</i> and <i>E. coli</i> O157:H7)		
Combined with chlorine decontamination	Treatment time can be increased to bring temperature to sublethal point without damaging the food, and thus increase decontamination efficacy	Huang, T.-S. et al., 2006
Fresh-cut Royal Gala apples and romaine lettuce (inoculated with <i>E. coli</i> O157:H7 and <i>Salmonella</i>)		
120 and 170 kHz	Combination with chlorine dioxide increased decontamination	Xu, C., 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 <i>Salmonella typhimurium</i>, <i>L. monocytogenes</i>, and <i>E. coli</i>		
25, 32-40, and 62-70 kHz for 30 min	Frequency of ultrasound treatment had no significant effect on decontamination efficiency	Seymour, I. J. et al., 2002

As summarized in Table 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 to 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, mint and other herbs. They reported that ultrasound treatment in the range 25 to 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.

Recently, the effects of ultrasound treatment on fruit decay and the physiological quality of strawberries were described by Cao et al. (2010). They reported that a 40 KHz ultrasound treatment resulted in a significant decrease in decay incidences and number of microorganisms. Further, the fresh quality of strawberries was maintained in terms of firmness, total soluble solids, vitamin C and titratable acidity. They concluded that ultrasound treatment possesses the potential ability to extend 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% PPO enzymes [Jang, J. H. et al., 2009]. It was shown that ultrasound technology could inhibit microorganisms and enzymes, prolonging shelf life and maintaining the quality of fresh-cut apples. However, other studies have shown relatively low inactivation of microorganisms and enzymes [Sala, F. J. et al., 1999]; therefore, it is widely accepted that ultrasound alone is not an effective method for inactivating bacteria in food [Piyasena, P. 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.

Acidic Electrolyzed Water

Acidic electrolyzed water (AcEW) is a new concept technology that was developed in Japan and has been classified as “functional water.” Some scientists use the alternative term electrolyzed oxidizing water (EOW) [Al-Haq, M. I. 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, Y.-R. et al., 2008].

The utilization of this technology on fresh-cut fruits and vegetables by microbial decontamination is summarized in Table 6.

Table 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 <i>E. coli</i> O157:H7)		
AcEW (pH 2.7), 68-70 mg	1 log cfu cm ⁻² reduction	Wang, H. U.

L ⁻¹ free chlorine, 8 min		A. et al., 2008
Fresh-cut cabbage		
AcEW (pH 2.5-2.7), 20-40 mg kg ⁻¹ available chlorine	Reduced <i>E. coli</i> by about 1 log CFU g ⁻¹	Achiwa, N. 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, S. 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 immediately supplied to consumers	Achiwa, N. et al., 2003
Fresh-cut leaves of romaine or iceberg lettuce (inoculated with <i>E. coli</i> O157:H7)		
AcEW (pH 2.6), 50 ppm free available chlorine	Reductions of less than 1 log CFU g ⁻¹	Keskinen, L. A. et al., 2009
Fresh-cut lettuce and fresh whole spinach leaves (inoculated with <i>E. coli</i> O157:H7, <i>Salmonella Typhimurium</i>, and <i>L. monocytogenes</i>)		
AcEW, alkaline EW water and deionized water	Alkaline EW 3-min treatment reduced 3 tested pathogens	Park, E. J. et al., 2008
Fresh-cut lettuce (inoculated with <i>L. monocytogenes</i>)		
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 to 240 ppm of Cl ₂ , reducing <i>L. monocytogenes</i> and <i>E. coli</i> O157:H7 by 1.5 log CFU g ⁻¹	Koseki, S. et al., 2004
Fresh-cut lettuce leaves (inoculated with <i>L. monocytogenes</i> and <i>E. coli</i>)		
AcEW (45 ppm residual chlorine) compared to chlorinated water	The difference between bactericidal activity of AcEW and chlorinated water was not significant	Park, C.-M. et al., 2001
Fresh-cut cabbage and lettuce		
AcEW, 150 ppm NaOCl and tap water	Loss in quality of AcEW treated cabbage and lettuce was equivalent to NaOCl and tap water treatment	Koseki, S.; Itoh, K., 2001
Fresh-cut lettuce and cabbage		
AcEW	Decrease at 1, 5, and 10°C storage decreased microbial populations	Koseki, S.; Itoh, K., 2001
Fresh-cut cilantro		
AcEW, 24% NaOCl, deionized water	NaOCl and de-ionized 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, H. et al., 2004
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, H., 1999
Green onion and tomato (inoculated with <i>E. coli</i> O157:H7, <i>Salmonella typhimurium</i>, and <i>L. monocytogenes</i>)		
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, E. J. 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, N. et al., 2004
Fresh-cut mixed leafy greens (spinach and lettuce) (inoculated with <i>E. coli</i> O157:H7, <i>Salmonella</i>, and <i>L. monocytogenes</i>)		
AcEW (pH 2.1), 30 to 35 ppm free chlorine	oxygen reduction potential 1100 mV, 2.1 to 2.8 log CFU g ⁻¹ reduction	Stopforth, J. D. et al., 2008
Fresh-cut salad: carrot, endive, iceberg lettuce, 'Four seasons' salad and corn salad		
NEW (pH 8.6), 50 ppm free chlorine	Reducing in amount of free chlorine used to disinfect fresh-cut, with same microbial reduction effectiveness as sodium hypochlorite	Abadias, M. et al, 2008
Fresh-cut spinach, lettuce (inoculated with <i>E. coli</i>, <i>Salmonella typhimurium</i>, <i>Staphylococcus aureus</i>, <i>L. monocytogenes</i>, and <i>Enterococcus faecalis</i>)		
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, J. L. et al., 2008

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

An emerging non-thermal 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 can be generated by electrical discharge [Song, H.P. et al., 2009]. When a gas passes through plasma, the gas become 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 [Critzner, F. et al., 2007; Chunqi, J. et al., 2009] by oxidation, although the exact mechanism of microbial cell inactivation is not fully understood [Fernandez-Gutierrez, S. A. 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 cost 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, B. et al., 2011].

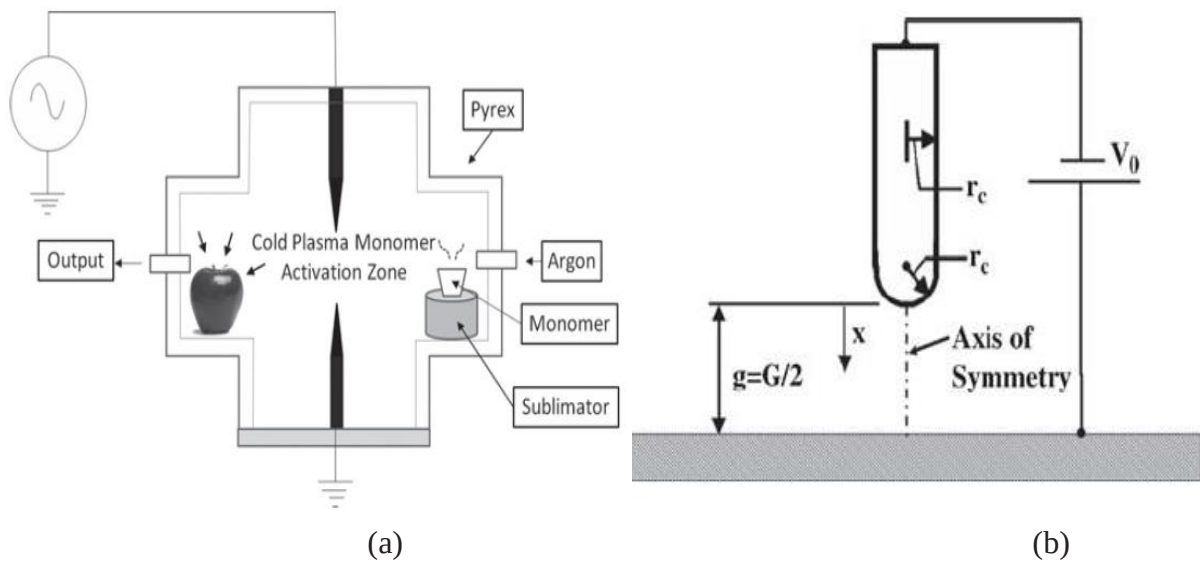


Figure 1. (a) Schematic illustration of an experiment utilizing cold plasma to treat red delicious apples; (b) Simplified model used to approximate the on-axis electric field in Fig. 1. (a) Parameter r_c is the radius of curvature of the needle tip as described by Fernandez-Gutierrez et al. [Song, H.P. et al., 2009].

For the calculation of electric field intensity E of the needle as illustrated in the Figure 1:

$$E_x(x) = E(x) = \frac{-2gV_0}{\ln\left(\frac{4g}{r_c}\right)[g(2x+r_c)-x^2]} \quad \text{equation 15}$$

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 non-attaching (electropositive) gas such as argon, it can be written as:

$$N(x) = N(0) \exp\left[\int_0^x \alpha(E(x)) dx\right] \quad \text{equation 16}$$

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

$$\frac{\alpha}{p} = A \exp\left(-\frac{C}{E/p}\right) \quad \text{equation 17}$$

with $A = 1200 \text{ m}^{-1} \cdot \text{torr}^{-1}$
 $C = 20000 \text{ V} \cdot \text{m}^{-1} \cdot \text{torr}^{-1}$

where p is the pressure in torr, and the E/p range for A and C is $C/2 < (E/p) < 3C$ [Fernandez-Gutierrez, S. A. et al., 2010].

The term cold plasma is a relative term which in the context of food processing refers to the ability to generate and apply the plasma nonthermally [Niemira, B. A.; Sites, J., 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, N. N. et al., 2011; Knorr D. et al., 2011]; unfortunately, information about the application of cold plasma on fruit and vegetable products is largely lacking. Table 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 allowing microbial inactivation at low temperature by generating free radicals in the plasma environment, presents uniform treatment, and diffuse into complicated structures with 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, M. et al., 2008].

Table 7. Studies on microbial inactivation of fruit and vegetables using cold plasma

Conditions	Results	Author
Mango and melon (cut fruit surface inoculated <i>Escherichia coli</i>, <i>Saccharomyces cerevisiae</i>, <i>Pantoea agglomerans</i>, and <i>Gluconacetobacter liquefaciens</i>)		
8 kV, 30 kHz	3 log reduction	Perni, S. et al., 2008
Golden Delicious apple (inoculated <i>Salmonella Stanley</i> and <i>Escherichia coli</i> 0157:H7)		
15 kV, 60 Hz	3.4 to 3.6 log reduction	Kim, B. et al., 2011
Golden Delicious apple (inoculated with <i>Listeria innocua</i>)		
10 kV, 115 - 150 mA	0.39 – 1,1 log reduction	Niemira et al. 2005, cited in Niemira & Sites, 2008
Seeds: tomato, wheat, bean, chick pea, soy bean, barley, oat, rye, lentil and corn (inoculated with <i>Aspergillus paraciticus</i> 798. and <i>Penicillium</i> MS 1982)		
20 kV, 1 kHz	3 log reduction	Selcuk, M. et al., 2008
Almond (inoculated with <i>E. coli</i>)		
30 kV, 2 kHz	5 log reduction	Deng, S. et al., 2007
Peanut and pistachio (inoculated with <i>Aspergillus parasiticus</i> and aflatoxins)		

20 kV, 1 kHz with total applied power approximately 300 W]	5 log reduction	Basaran, P. et al., 2088
Apple, cantaloupe, and lettuce (inoculated with <i>Escherichia coli</i> O157:H7, <i>Salmonella</i>, and <i>Listeria monocytogenes</i>)		
9 kV, 6 kHz	5 min treatment resulted in > 5 log reduction	Critzer, F. J. et al., 2007
Lettuce (inoculated with <i>Escherichia coli</i> ATCC 11775)		
5.7 kV RMS in Argon, 0,5;3.0 and 5.0 min	1.2 log reduction	Bermudez-Aguirre, D. et al., 2011

Based on the studies summarized in the Table 7, cold plasma has a promising future application for extending the shelf life of fresh-cut fruit and vegetables. This extended shelf life is attributed to the microbial disinfection of this technology at low temperature for the food surface by generating free radicals that inactivate microorganisms, resulting in food products free of any residues and retaining the fresh-like characteristics of the fresh-cut products.

Final remarks

Current techniques used by the fresh-cut industries 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 for 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. When discussing the shelf life extension of fresh-cut products using nonthermal technology, it 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 to extend shelf life and ensure the safety of products, which has led to several promising nonthermal technologies for later advanced commercial application, while some are commercially available today. The summarized potential of commercial nonthermal technologies in prolonging fresh-cut product shelf life is shown in Table 8.

Table 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 fresh-like 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 been proven to be effective in	+++

	extending shelf life and quality	
Ozone	Has proven to be an effective decontamination agent as compared to chlorine, and is an environmentally friendly disinfectant	++
Ultraviolet	Low-dose ultraviolet has proven to be 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, and is an environmental friendly disinfectant	+
Cold Plasma	Microbial inactivation by generating free radicals at low temperature resulting in food products free of any residues	+

To summarize, most studies have reported that nonthermal processing is a promising mean of extending shelf life, enhancing safety and maintaining the fresh-like 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 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 fresh-cut fruit and vegetable industries, forthcoming work focusing on extensive scale up and guidelines describing potential nonthermal processes for use commercially to extend the shelf life of fresh-cut products are definitely required.

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