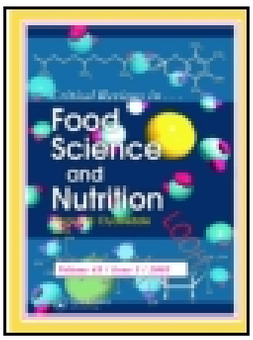

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Advances in postharvest technologies to extend the storage life of minimally processed fruits and vegetables

Asgar Ali[a], Wei Keat Yeoh[a], Charles Forney[b], and Mohammed Wasim Siddiqui[c]

[a]Centre of Excellence for Postharvest Biotechnology (CEPB), School of Biosciences, The University of Nottingham Malaysia Campus, Semenyih, Selangor, Malaysia; [b]Agriculture and Agri-Food Canada, Kentville Research and Development Centre, 32 Main Street, Kentville, Nova Scotia, Canada; [c]Department of Food Science and Postharvest Technology, Bihar Agricultural University, Sabour, Bhagalpur, Bihar, India

ABSTRACT

Minimally processed fresh produce is one of the fastest growing segments of the food industry due to consumer demand for fresh, healthy, and convenient foods. However, mechanical operations of cutting and peeling induce the liberation of cellular contents at the site of wounding that can promote the growth of pathogenic and spoilage microorganisms. In addition, rates of tissue senescence can be enhanced resulting in reduced storage life of fresh-cut fruits and vegetables. Chlorine has been widely adopted in the disinfection and washing procedures of fresh-cut produce due to its low cost and efficacy against a broad spectrum of microorganisms. Continuous replenishment of chlorine in high organic wash water can promote the formation of carcinogenic compounds such as trihalomethanes, which threaten human and environmental health. Alternative green and innovative chemical and physical postharvest treatments such as ozone, electrolyzed water, hydrogen peroxide, ultraviolet radiation, high pressure processing, and ultrasound can achieve similar reduction of microorganisms as chlorine without the production of harmful compounds or compromising the quality of fresh-cut produce.

KEYWORDS

Fresh-cut; spoilage; storage life; chlorine; chemical treatment; physical treatment

Introduction

Disinfecting and washing are important processes to remove dirt, pesticide residues and spoilage microorganisms, which are detrimental to the quality of fresh-cut fruits and vegetables (Gil et al., 2009). Currently, more than three quarters of the food industry depends on the application of chlorine to kill pathogens and spoilage organisms due primarily to its reliable availability and low application cost (Gil et al., 2009). However, the formation of carcinogenic compounds such astrihalomethanes can pose a serious threat to human health and the environment. Thus, the drawback of chlorine usage has urged the development of alternative sanitizing methods to ensure the safety and quality of fresh-cut fruits and vegetables. Over the years, many alternative chemicals and physical disinfection treatments have been evaluated for their efficacy to reduce the population of pathogens and extend the shelf-life of fresh-cut produce including their impact on the texture, visual appearance, flavor and nutritional value (Rico et al., 2007). In addition, the development of edible coatings also provides new technologies that can contribute to the preservation of the quality and safety of fresh-cut fruits and vegetables. Therefore, this review will discuss the effectiveness of chlorine and compare it to alternative technologies for washing, sanitizing and preserving fresh-cut produce.

Chlorine

Chlorine is typically added as a sanitizing agent to water used to wash fresh-cut produce. The recommended total chlorine concentrations in processing water range from 50 to 200 mg L^{-1} with the maintenance of 2–7 mg L^{-1} free residual chlorine after contact (Delaquis et al., 2004). The pH of chlorine based sanitizers must be adjusted to 6–7.5 to maintain a high level of hypochlorous acid and minimize corrosion of equipment (Rico et al., 2007; Van Haute et al., 2013). Existing data about the efficiency of chlorine solutions as a sanitizer for fresh-cut produce decontamination at the recommended concentration are very limited since it can generally reduce the population of spoilage microorganisms by only 1–2 log CFU g^{-1} (Alegria et al., 2009; Van Haute et al., 2013).

A study conducted by Akbas and Olmez (2007) reported that the initial population of mesophilic, psychotropic, and Enterobacteriaceae bacteria in fresh-cut iceberg lettuce was significantly reduced by 1.7, 2.0, and 1.6 log CFU g^{-1}, respectively, immediately after dipped in 100 mg L^{-1} chlorine solution for 2 min. The changes in physicochemical properties, including ascorbic acid and β-carotene, in chlorine-treated lettuce were insignificant when compared to that of untreated lettuce throughout 12 d of storage at 4°C storage. Although the contact time and concentration of the chlorine solution used were different, the efficacy of chlorine to reduce the initial microbial loads in fresh-cut iceberg lettuce was also reported by Delaquis et al. (2004), Vandekinderen et al. (2009) and Wulfkuehler et al. (2013). Additionally, the sensory attributes of iceberg lettuce were not adversely affected by chlorine (Delaquis et al., 2004; Vandekinderen et al., 2009). Similarly, a reduction of 1–2 log CFU g^{-1} of various pathogenic and spoilage

CONTACT Asgar Ali Asgar.Ali@nottingham.edu.my Centre of Excellence for Postharvest Biotechnology (CEPB), School of Biosciences, The University of Nottingham Malaysia Campus, Semenyih 43500, Selangor, Malaysia.

microorganisms was also reported in chlorinated fresh-cut lettuce (Allende et al., 2008; Posada-Izquierdo et al., 2013), escarole (Allende et al., 2008) and carrot (Klaiber et al., 2005).

In contrast, López-Gálvez et al. (2010) reported that although the initial counts of native microflora were reduced in fresh-cut melon following dipping in 150 mg L^{-1} of chlorine for 1 min, the microbial populations increased gradually and showed no significant differences when compared with those dipped in tap water throughout the 10 d of storage at 5°C. The inability of chlorine to inhibit the growth of microorganisms was accompanied by a decline in total ascorbic acid content of chlorine-treated fresh-cut melon during storage (López-Gálvez et al., 2010). Similarly, the population of mesophilic bacteria on fresh-cut kiwi dipped in 150 mg L^{-1} of sodium hypochlorite solution for 2 min showed no significant differences as compared to samples dipped in distilled water after 10 d of storage at 4°C (Beirao-da-Costa et al., 2014). Waghmare and Annapure (2015) reported that the storage life of fresh-cut cilantro treated with 100 mg L^{-1} sodium hypochlorite alone for 2 min had the shelf life up to 20 d and the combination of chlorine and MAP extended the shelf life up to 25 d at 5°C. The control sample had its shelf life up to 10 d at same temperature.

A relatively constant free chlorine level must be maintained during commercial fresh-cut wash operations to ensure disinfection efficiency of the sanitizer and prevent cross contamination. However, the increase in chemical oxygen demand (COD) due to the accumulation of plant debris and exudates in the washing solution often leads to increase chlorine consumption, thus increasing the potential of pathogen survival and cross contamination (Luo et al., 2012). For instance, Yang et al. (2012) reported that the survival of *E. coli* O157:H7 was significantly enhanced when the concentration of free chlorine in wash solutions was depleted from 35 mg L^{-1} to near zero after washing of 3.6 kg of shredded lettuce with 40 L of sanitizing solution. The depletion of free chlorine concentration due to the presence of high organic loads was also reported in the washing solution of fresh-cut spinach (Gómez-López et al., 2014) and lettuce (Van Haute et al., 2013).

Continuous replenishment of chlorine into high organic wash water can result in the formation of chlorine off-gas and carcinogenic halogenated compounds such as trihalomethanes and haloacetic acid in the processing environment (Luo et al., 2012; Yang et al., 2012). The use of chlorine as a disinfectant agent in the fresh-cut industry has been banned in several European Union countries such as Germany, Switzerland, the Netherlands, Denmark and Belgium due to the possible formation of these harmful disinfection by-products (Rico et al., 2007; Van Haute et al., 2013). Although, López-Gálvez et al. (2010) reported thtrihalomethanemethane level in frelettuce, washed with 100 mg L^{-1} sodium hypochlorite and high concentrations of organic matter (Choxygen oxygen demand, i.e., COD 700 mg L^{-1}) was negligible, the concentration of trihalomethanes in the process water was beyond the authorized limit set by the European legislation (100 μg L^{-1}). Similarly, unacceptable levels of trihalomethanes were also detected in process water of fresh-cut spinach (Gómez-López et al., 2014) and lettuce (Van Haute et al., 2013). Although some studies demonstrated that the level of trihalomethanes in fresh-cut produce washed with chlorinated water was below the legislated limit, maintaining a stable free chlorine level requires periodic monitoring and intervention during fresh-cut produce processing. Process control failure due to the rapid depletion of free chlorine in the wash system in the presence of high organic loads has urged the food industry to develop economically viable, safe and environmentally friendly alternative technologies to prolong the storage life of fresh-cut produce.

Other chemical treatments

Ozone

Ozone is a chemically active triatomic allotrope of elemental oxygen, which can be generated by ultraviolet radiation and corona discharge. High energy irradiation can split diatomic oxygen into free radicals that rapidly combine with oxygen to form ozone (Guzel-Seydim et al., 2004). In 2001, the U.S. Food and Drug Administration (FDA) declared ozone to be a Generally Recognized as Safe (GRAS) substance for the commercial use as a disinfectant and sanitizer in food handling (Aguayo et al., 2014; Khadre et al., 2001). It should be noted that ozone can rapidly decompose to diatomic oxygen, leaving no residue on food and hence provides an alternative to chlorine based washing solutions. Ölmez and Akbas (2009) revealed that waste water collected from an ozonated wash system of fresh-cut green leaf lettuce had significantly lower COD and a lower recovery of mesophilic bacteria when compared to waste water treated with chlorine. Garcia et al. (2003) also suggested that ozonated waste water can be reused and recycled to reduce excessive water consumptions in the industry. The application of ozone has received commercial interest in the food industry due to its effectiveness to extend the shelf life of fresh or fresh-cut produce by inhibiting the growth of microorganisms (Beltrán et al., 2005a; Selma et al., 2007; Silveira et al., 2010; Venta et al., 2010), preventing decay (Nadas et al., 2003; Palou et al., 2003; Tzortzakis et al., 2008) and removing pesticides and fungicides that reside on the surface of fruits and vegetables (Ikeura et al., 2011; Karaca et al., 2012; Whangchai et al., 2011).

As shown in Table 1, ozone in the aqueous or gaseous state has been applied to extend the shelf life of fresh-cut produce due to its broad antimicrobial effect. For instance, ozonated water at the concentration of 4 mg L^{-1} significantly reduced the population of mesophilic, psychotropic and Enterobacteriaceae bacteria in fresh-cut iceberg lettuce by 1.7, 1.5, and 1.6 log CFU g^{-1}, respectively, after a 2 min treatment (Akbas and Olmez, 2007). These authors reported that changes in the quality and nutritional attributes of ozonated fresh-cut iceberg lettuce were comparable to that of untreated lettuce throughout storage. Similarly, Zhang et al. (2005) demonstrated that the microbial load of fresh-cut celery treated with 0.18 mg L^{-1} ozonated water for 10 min was reduced by 1.15 log CFU g^{-1} after 9 d of storage at 4°C. Quality of ozone treated fresh-cut celery was maintained throughout storage and the respiration rate and enzymatic activity of polyphenol oxidase (PPO) were significantly reduced when compared to the control. The population of native microflora was also reduced in ozonated fresh-cut carrot (Chauhan et al., 2011), cilantro (Wang et al., 2004), and green leaf lettuce (Ölmez and Akbas, 2009).

Table 1. Chemical treatments and their effects on quality of fresh-cut fruits and vegetables.

Treatment	Parameters	Fresh-cut fruits/ vegetables	Results	References
Ozone	Ozonated water: 2 μL L^{-1} for 2 min Storage: 12 d, 4°C	Lettuce	Ozone treatment significantly reduced the population of mesophilic, psychrotrophic and Enterobacteriaceae and maintained better sensory quality during 9 d of storage.	Ölmez & Akbas, 2009
	Ozonated water: 4 mg L^{-1} for 2 min Storage: 12 d, 4°C	Iceberg lettuce	Ozone significantly reduced the initial loads of mesophilic, psychrotrophic, and Enterobacteriaceae counts by 1.7, 1.5, and 1.6 log CFU g^{-1}, respectively.	Akbas & Olmez, 2007
	Ozonated water: 5 μL L^{-1} for 5 min Storage: N/A	Lettuce	The population of *Shigellasonnei* inoculated in shredded lettuce was reduced by 1.8 CFU g^{-1} after dipped in ozonated water.	Selma et al., 2007
	Ozonated water: 1 mg L^{-1} for 1 min Storage: 10 d, 4°C	Lettuce	Ozone treatment prevented browning of fresh-cut lettuce by inhibiting browning enzymes (PPO and POD).	Rico et al., 2006
	Ozonated water: 0.4 mg L^{-1} for 3 min Storage: 10 d, 5°C	Tomato slices	Ozone treated tomato slices achieved the best firmness retention and microbial quality after 10 d of storage.	Aguayo et al., 2014
	Ozonated water: 10 mg L^{-1} for 10 min Storage: 30 d, 6 ± 1°C, 85% RH	Carrot sticks	Ozone treatment significantly reduced the population of mesophilic, yeasts and molds and coliforms by 3.2, 1.8, and 2.4 log CFU g^{-1}, respectively, after 30 d of storage.	Chauhan et al., 2011
Ozone	Ozonated water: 0.4 mg L^{-1} for 3 min Storage: 10 d, 5°C	Melon	Ozone treatment significantly reduced the population of spoilage microorganisms especially bacteria. However, the changes in the population of fungus was not significant.	Silveira et al., 2010
	Ozonated water: 20 mg L^{-1} for 3 min Storage: 14 d, 4°C	Potato	Ozone treatment alone was insufficient to inhibit the growth of spoilage microorganisms. A combination of ozone and antimicrobial water (Tsunami^{TM}) significantly reduced the population of lactic acid bacteria, coliforms and anaerobic microorganisms by 3.3, 3.0, and 1.2 log CFU g^{-1}.	Beltrán et al., 2005b
	Gaseous ozone: 9.0 μL L^{-1} for 6 h Storage: 19 ± 1°C, 95% RH	Bell pepper	The population of inoculated *E.coli* O157:H7, *Salmonella Typhimurium*, and *Listeria monocytogenes* was reduced by 2.9, 2.6, and 3.1 log CFU g^{-1} after ozone treatment.	Alwi & Ali, 2014
	Gaseous ozone:0.7 μL L^{-1} for 3 min Storage: 14 d, 8 ± 1°C	Peppers	The population of mesophiles, psychrotrophes, and yeast and molds was reduced by 2.5, 3.3, and 1.8 log CFU g^{-1}.	Horvitz & Cantalejo, 2012
	Gaseous ozone: 9.0 μL L^{-1} for 20 min Storage: N/A	Papaya	The population of mesophiles and coliforms were only reduced by 0.3 and 1.1 log CFU g^{-1}.	Yeoh et al., 2014
	Gaseous ozone: 0.73 mmol for 20 min Storage: N/A	Pineapple Banana Guava	Ozone treatment improved the antioxidant capacity of fresh-cut fruits.	Alothman et al., 2010
Electrolyzed water	Acidic electrolyzed water FCC:16.8 mg L^{-1} pH: 2.5 ORP: +1130 mV Storage: 14 d, 0°C	Cilantro	Initial loads of aerobic bacteria and Enterobacteriaceae were reduced significantly after washed with acidic electrolyzed water. However, the treatment resulted in loss of firmness and high electrolyte leakage.	Wang et al., 2004
	Acidic electrolyzed water FCC: 100 mg L^{-1} pH: 3.0 ORP: +1128 mV Storage: 5 d, 4°C	Apple	The growth pathogenic bacteria, inoculated on samples, was reduced by 1.2–1.6 log CFU g^{-1} after 5 d of storage.	Graça et al., 2011
	Acidic electrolyzed water FCC: 45 mg L^{-1} pH:2.7 ORP: +1150 mV Storage: 21 d, 4°C	Apple	Treatment was effective to inhibit the growth of spoilage and pathogenic bacteria. However, the firmness of treated samples was lower than control at the end of storage.	Wang et al., 2007
	Neutral electrolyzed water FCC: 100 mg L^{-1} pH: 7.0 ORP: +900 mV Storage: 14 d, 5°C	Kailan hybrid broccoli	The growth of *E.coli* and *S. Enteritidis* inoculated on samples was significantly reduced by 2.6 log CFU g^{-1} after treatment. The antimicrobial effect of electrolyzed water was prolonged as the microbial counts of *E.coli* and *S. Enteritidis* were lower than control at the end of storage.	Martínez-Hernández et al., 2015a
Electrolyzed water	Neutral electrolyzed water FCC: 200 mg L^{-1} pH: 8.2 ORP: +846 mV Storage: 3 d, 4°C	Lettuce Catalogna chicory	The population of aerobic bacteria and Enterobacteriaceae was reduced by approximately 1.7 log CFU g^{-1} after 5 min of treatment.	Pinto et al., 2015
	Neutral electrolyzed water FCC: 100 mg L^{-1} pH: 7 ORP: +900 mV	Broccoli	The antimicrobial efficacy of electrolyzed water containing 100 mg L^{-1} against the growth of mesophiles, psychrotroph, Enterobacteriaceae, and yeasts and molds during storage was comparable to that of 100 mg L^{-1} sodium hypochlorite solution.	Navarro-Rico et al., 2014

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Table 1. (Continued).

Treatment	Parameters	Fresh-cut fruits/ vegetables	Results	References
	Storage: 19 d, 5°C			
	Neutral electrolyzed water FCC: 30 mg L^{-1} pH: 7.9 ORP: N/D Storage: N/A	Iceberg lettuce	Electrolyzed water containing 30 mg L^{-1} free chlorine reduced the microbial loads by 1.6 log CFU g^{-1} which was comparable to the reduction achieved with chlorinated water at 200 mg L^{-1}.	Vandekinderen et al., 2009
	Neutral electrolyzed water FCC: 50 mg L^{-1} pH: 8.6 ORP: N/D	Iceberg lettuce Carrot Four season Endive Corn salad	The antimicrobial efficacy of neutral electrolyzed water containing about 50 mg L^{-1} free chlorine against pathogenic bacteria was found to be as effective as 120 mg L^{-1} chlorinated water.	Abadias et al., 2008
	Neutral electrolyzed water FCC: 60 mg L^{-1} pH: 6.5 ORP: 750 – 900 mV Storage: 2 d, 7°C	Lettuce	The growth of spoilage microorganisms in samples treated with electrolyzed water containing 60 mg L^{-1} was reduced during storage and the reduction was comparable to that of 120 mg L^{-1} chlorinated water.	Rico et al., 2008
Electrolyzed water	Neutral electrolyzed water FCC: 100 mg L^{-1} pH: 7.0 ORP: +900 mV Storage: 19 d, 5°C	Broccoli	The microbial loads of mesophiles, psychrotroph, Enterobacteriaceae, and yeasts and molds were reduced by 1.8, 3.0, 1.9, and 0.8 log CFU g^{-1} after 19 d of cold storage.	Martínez-Hernández et al., 2013
	Neutral electrolyzed water FCC: 100 mg L^{-1} pH: 7.0 ORP: N/D Storage: 11 d, 5°C	Mizuna baby leaves	The inhibitory effect of neutral electrolyzed water against the growth of spoilage microorganisms in samples was similar to that of acidic electrolyzed water.	Tomás-Callejas et al., 2011
	Slightly acidic electrolyzed water FCC: 20 mg L^{-1} pH: 6 ORP: +800 mV Storage: 14 d, 4°C	Cilantro	Treatment reduced the initial loads of aerobic bacteria by 5.4 log CFU g^{-1} without affecting the quality (electrolyte leakage and firmness) of samples at the end of storage.	Hao et al., 2014
	Slightly acidic electrolyzed water FCC: 68 mg L^{-1} pH: 2.5 ORP: +1127 mV + Alkaline electrolyzed water FCC: N/D pH: 11.7 ORP: −824 mV Storage: N/A	Cilantro	The reduction in the native microflora (total aerobic bacteria, coliforms and yeasts and molds) of fresh-cut cilantro was observed when subjected to sequential washes of alkaline electrolyzed water and followed by acidic electrolyzed water.	Hao et al., 2015
Electrolyzed water	Alkaline electrolyzed water and 1% citric acid FCC: N/D pH: 11.3 ORP: −810 mV Storage: 15 d, 4°C	Carrot	A reduction (approximately 3.7 log CFU g^{-1}) in total microbial and yeasts and molds counts was recorded after treatment.	Rahman et al., 2011
	Concentration: 3% (v/v) for 5 min Storage: 8 d, 5°C	Pear	The population of *E. coli*, *L. innocua* and *Zygosaccharomyces bailii* inoculated on pear disc was reduced by 2.5, 1.4 and 0.3 log CFU g^{-1} after H_2O_2 treatment.	Schenk et al., 2012
	Concentration: 167 mg L^{-1} for 3 min Storage: 14 d, 5°C	Watercress	H_2O_2 treatment significantly inhibited the initial loads of psychrotroph, mesophiles, and Enterobacteriaceae. However, the treatment decreased the total antioxidant capacity of samples.	Hinojosa et al., 2013
	Concentration: 0.4 ppm for 2 min Storage: 7 d, 12°C	Iceberg lettuce	The initial total viable and yeast counts was reduced after H_2O_2 treatment. However, the antimicrobial effect of H_2O_2 was not prolonged during subsequent storage as microbes proliferated rapidly.	Gopal et al., 2010
	Concentration: 3% (v/v) for 1 min Storage: 7 d, 4°C	Mushroom	H_2O_2 treatment inhibited the growth of mesophiles, psychrotroph, and *Pseudomonas* throughout storage.	Cliffe-Byrnes & O'Beirne, 2008
	Concentration: 0.6% (v/v) for 2 min Storage: 18 d, 4°C	Water chestnut	H_2O_2 treatment delayed the development of disease caused by microorganisms. Also, the development of discolorization was delayed by inhibiting the activity of PPO.	Peng et al., 2008
H_2O_2	Concentration: 50 mg L^{-1} for 1 min Storage: 10 d, 5°C	Melon	The antimicrobial efficacy of H_2O_2 against Enterobacteriaceae was higher than that of chlorine. Also, H_2O_2 treated samples retained better firmness than chlorine washed samples.	Silveira et al., 2008
	Concentration: 0.4 M for 1 min Storage: 8 d, 10°C	Tomato	The count of spoilage microorganisms enumerated from H_2O_2 treated samples was 55% lower than control. However, a decline in the content of total phenols and antioxidant activity was observed.	Kim et al., 2007

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Table 1. (Continued).

Treatment	Parameters	Fresh-cut fruits/ vegetables	Results	References
	Concentration: 2.5% (v/v) for 5 min Storage: 7 d, 5°C	Melon	H_2O_2 treatment significantly inhibited the growth of spoilage (mesophiles and yeasts and molds) and pathogenic (*E. coli* O157: H7 and *L. monocytogenes*) microorganisms.	Ukuku et al., 2005
	Concentration: 1.0% (v/v) for 5 min Storage: 15 d, 5°C	Honeydew Cantaloupe	*Salmonella spp*. inoculated in fresh-cut honeydew and cantaloupe was reduced by 1.3 and 1.7 log CFU g^{-1} after H_2O_2 treatment.	Ukuku, 2004

The reduction of initial microbial loads of fresh-cut produce is mainly due to the antimicrobial effect of ozone that oxidizes the thiol group of cysteine residues in bacterial enzymes involved in respiration and maintenance of the homeostatis environment (Guzel-Seydim et al., 2004). Also, the strong oxidizing potential of ozone can degrade the bacterial cell envelope, which consists of various components such as polyunsaturated fatty acids, glycoproteins and glycolipids (Khadre et al., 2001). Hence, a chain reaction triggered by ozone often leads to cell lysis, subsequent leakage of cell contents and rapid oxidation of cellular protein.

Although Aguayo et al. (2006) reported that cyclic exposure to 4 μL L^{-1} of gaseous ozone for 30 min every 3 h significantly reduced respiration rate and ethylene emission of sliced tomato throughout storage, there was little reduction of yeast population. Fresh-cut melon treated with 0.4 mg L^{-1} ozonated water for 5 min also had a little reduction in the population of yeasts and molds, while the respiration rate increased during storage. Adverse effects of ozone on ascorbic acid and phenolic content were also reported in fresh-cut carrot (Chauhan et al., 2011) and iceberg lettuce (Beltrán et al., 2005a), which accompanied a significant reduction of microbial populations.

Inconsistent results obtained in various ozone experiments may be due to the leaching of plant exudates from the cut surface of fresh-cut produce. Ozone can readily react with organic compounds and can be inactivated before it can react with microorganisms on the cut surface (Alexandre et al., 2011; Ketteringham et al., 2006). Besides, various degrees of processing (peeling, cutting, and shredding) may have transferred microorganisms from the skin surface to the cracks and crevices of cut fruits and vegetables. The attachment of bacteria on the uneven surfaces of fresh-cut commodities can reduce the contact of ozone with microorganisms and hence affect the overall effectiveness of ozone treatment. Discrepancies regarding the efficacy of ozone on the growth of microorganisms may further suggest that the antimicrobial effect of ozone is selective and dependent on the type of bacteria strains. It should be noted that gram-negative bacteria such as *Escherichia coli* and *Salmonella* have a thinner peptidoglycan layer on the cell wall than gram-positive bacteria. Hence, gram negative bacteria are more vulnerable to the microbicidal action of ozone. In addition, the low pH of fresh-cut produce can affect the efficiency of ozone since it is more stable and effective in oxidizing bacteria cell envelops at low pH (Khadre et al., 2001). Therefore, standardization of experimental (ozone generation, concentration, and exposure time) and environmental conditions (temperature, relative humidity, and pH) have to be carried out to better understand the mode of action and effects of ozone in different fresh-cut commodities.

Also, since the exposure to ozone above a certain concentration can cause toxicity symptoms to the operator, the FDA has recommended that workers shall not be exposed to an average concentration of more than 0.05 ppm of ozone for 8 h (Miller et al., 2013). Therefore, the establishment of ozone technology in the fresh-cut industry may require a cautious system design and process operation in order to comply with the established health standards recommended by the FDA.

Electrolyzed water

Electrolyzed water was originally developed in Japan and Russia to decontaminate and regenerate process water and disinfect medical instruments (Hricova et al., 2008; Huang et al., 2008). The application of electrolyzed water as an eco-innovative sanitizer has gained interest in the fresh-cut industry considering its potential advantages, including strong bactericidal effect, negligible residual contamination, minimal corrosion of processing equipment or skin irritation and low operational cost (Hao et al., 2015; Hricova et al., 2008; Mukhopadhyay and Ramaswamy, 2012). Electrolyzed water is generated by electrolyzing a dilute sodium chloride (NaCl) solution with a current across an anode and cathode that are separated by a bipolar membrane. Electrolysis of the salt solution can produce reduced substances with strong biocidal activity such as hypochlorous acid (HOCl), hypochlorite ion (OCl-), hydroxyl (OH-), and superoxide radicals (O2●-) (Abadias et al., 2008; Pinto et al., 2015; Posada-Izquierdo et al., 2014).

Ionization resulting from different current voltage at the anode will result in the formation of acidic electrolyzed water that has a pH range of 2–4, Oxidation reduction potential, i.e., ORP value >1000 mV and free chlorine concentration (FCC) of up to 50 mg L^{-1} (Abadias et al., 2008; Mukhopadhyay and Ramaswamy, 2012). Whereas, alkaline electrolyzed water with a pH range of 10–11.5 and an ORP value of −800 mV is formed at the cathode (Huang et al., 2008). In the absence of a bipolar membrane, the mixture of acidic and alkaline solutions produces neutral electrolyzed water, which is characterized by a pH range of 5–8.5, ORP value of 500–700 mV and FCC of 10–30 mg L^{-1} (Graça et al., 2011; Hao et al., 2015; Hricova et al., 2008).

Several studies have suggested that the high ORP of electrolyzed water causes a modification of metabolic fluxes and production of ATP in the bacterial cells due to the change in electron flow (Pangloli and Hung, 2011; Graça et al., 2011; Hricova et al., 2008). Subsequently, oxidation of sulfhydryl compounds in the presence of high ORP can inflict damage on the cell membrane and allow better penetrability of HOCl through the membrane resulting in bacteria necrosis (Huang et al.,

2008; Navarro-Rico et al., 2014). Besides high ORP, low pH of acidic electrolyzed water also can induce cell permeabilization, which allows the entry of HOCl into the bacterial cell. In the presence of HOCl, OH^{-1} radicals with strong antimicrobial activity are produced and induce the oxidative decarboxylation of amino acids to nitrites and aldehydes, which disrupts protein synthesis (Huang et al., 2008; Pinto et al., 2015).

Graça et al. (2011) reported that the application of acidic electrolyzed water (FCC: 100 mg L^{-1}; pH: 3.0; ORP: +1128 mV) significantly reduced the population of *E. coli, L. innocua*, and *S. choleraesuis* inoculated on apple slices by approximately 2.5, 1.2, and 1.4 log CFU g^{-1} after 30 min of treatment. The study showed that the antimicrobial effect of acidic electrolyzed water was prolonged as the growth of these pathogenic microorganisms was reduced by 1.2–1.6 log CFU g^{-1} after 5 d of storage at 4°C. The results obtained in the study support those of Wang et al. (2007) who also demonstrated a significant reduction of *E. coli* O157:H7 inoculated on fresh-cut apple after treatment with acidic electrolyzed water (FCC: 45 mg L^{-1}; pH: 2.7; ORP: +1150 mV) for 5 min. Besides the inhibition of pathogenic bacteria, it was also observed that the treatment significantly reduced the count of aerobic bacteria and yeasts and molds during 21 d of storage at 4°C. However, the lightness value and the firmness of fresh-cut apple washed with acidic electrolyzed water were lower in comparison to those of the control after 21 d of cold storage. Similarly, although the application of acidic electrolyzed water reduced the initial loads of aerobic bacteria and Enterobacteriaceae, the treatment had adverse effects on the physical properties of fresh-cut cilantro as shown by high electrolyte leakage and poor firmness retention after 14 d of storage at 0°C (Wang et al., 2004).

It has been speculated that the presence of high concentration of HOCl in low pH washing solution can impair the microsomal membrane and disrupt the cell wall structure (Wang et al., 2004). High concentration of free chlorine content in acidic electrolyzed water can also cause corrosive damage on the equipment after long exposure. It is worth noting that about 10–15% of the chlorine compounds in acidic electrolyzed water will exist in the form of chlorine (Cl_2) at pH below 4 (Hricova et al., 2008; Pangloli and Hung, 2011). Cl_2 is easily volatilized and can cause discomfort to the operators due to the pungent choking smell in the working environment. Considering the adverse effect of this technology on the quality of fresh-cut products and health and safety concerns in the processing plant, the application of acidic electrolyzed water may not be favored by the fresh-cut industry. Therefore, the application of neutral electrolyzed water may be a potential alternative to decontaminate fresh-cut fruits and vegetables.

High stability of neutral electrolyzed water due to low level of chlorine gas formed in near neutral pH (6–8) has been favored in the fresh-cut industry as it is less corrosive and hazardous to processing equipment and operators' health (Pangloli and Hung, 2011; Posada-Izquierdo et al., 2014). Navarro-Rico et al. (2014) reported that the microbial loads of mesophiles, psychrotrophes, Enterobaceriaceae, and yeasts and molds enumerated from fresh-cut kai-lan hybrid broccoli were approximately 1.7, 4.0, 0.9, and 4.0 lof CFU g^{-1} after washing with neutral electrolyzed water (FCC: 100 mg L^{-1}; pH:7; ORP +900 mV) for 2 min. In that study, the antimicrobial effect of the treatment was prolonged as the growth of spoilage microorganisms was inhibited during 19 d of storage at 5°C and the results obtained were comparable to those obtained with acidic electrolyzed water containing 70 mg L^{-1} free chlorine and 100 mg L^{-1} sodium hypochlorite solution. Authors also found that the activity of antioxidant enzymes such as ascorbate peroxidase (APX), guaicol peroxidase (GPX) and catalase (CAT), which induce plant defense mechanisms in response to biotic and abiotic stresses, were significantly increased in samples washed with neutral electrolyzed water. Tomas-Callejas et al. (2011) also showed that the use of neutral (FCC: 100 mg L^{-1}; pH: 7; ORP: +900 mV) and acidic (FCC: 40 mg L^{-1}; pH:3; ORP: +1100 mV) electrolyzed water had similar inhibitory effect on the growth of spoilage microorganisms enumerated from fresh-cut mizuna baby leaves. The reduction of total antioxidant capacity in samples washed with neutral electrolyzed water was lower in comparison to sample treated with acidic electrolyzed water during 11 d of storage at 5°C.

Martínez-Hernández et al. (2015a) observed a 1.6 log CFU g^{-1} reduction of *E. coli* and *S. enteritidis* on inoculated fresh-cut kalian hybrid broccoli following a 2 min exposure to neutral electrolyzed water (FCC: 100 mg L^{-1}, pH 7, ORP: +900 mV). Similarly, after a 5 min application of neutral electrolyzed water (FCC: 200 mg L^{-1}, pH 8.2, ORP: +846 mV), the native population of mesophilic aerobic and Enterobacteriaceae bacteria in fresh-cut catalogna chicory was significantly reduced (Pinto et al., 2015).The authors reported that the antimicrobial effect of neutral electrolyzed water was prolonged during cold storage, as the population of total mesophilic aerobic and Enterobacteriaceae bacteria was reduced by 0.9 and 2.0 log CFU g^{-1}, respectively, after 3 d of storage at 4°C. Several studies also reported that the microbial loads of spoilage and pathogenic microorganisms enumerated from fresh-cut iceberg lettuce (Vandekinderen et al., 2009) and lettuce (Abadias et al., 2008; Rico et al., 2008) were reduced by 1–2 log cycles after treatment with neutral electrolyzed water containing about 30–60 mg L^{-1} free chlorine. These studies have shown that the antimicrobial efficacy of neutral electrolyzed water was comparable to sodium hypochlorite solution. Although the use of neutral electrolyzed water offers several advantages in terms of food decontamination efficiency and health and safety aspects, antimicrobial activity of neutral electrolyzed water will be depleted over processing time if the system is not constantly supplied with H^+, HOCl, and Cl_2 by electrolysis (Huang et al., 2008). Also, chlorine will exist in the OCl^- form that has lower bactericidal activity than HOCl when the pH of the solution is 8 and above (Pangloli and Hung, 2011).

Another electrolyzed water generation system, which utilizes 3–6% (v/v) hydrochloric acid solution in an electrolytic cell without membrane separation produces slightly acidic electrolyzed water. This electrolyzed water shows promising antimicrobial effect in the fresh-cut industry as the solution contains about 95% HOCl, 5% OCl^-, and trace amounts of Cl_2 whilst the pH maintains at 4.5–6.5. For example, Hao et al. (2014) reported that the initial loads of aerobic bacteria was significantly reduced in fresh-cut cilantro after washing with slightly acidic electrolyzed water (FCC: 20 mg L^{-1}; pH:6; ORP: +800 mV) for 5 min. The treated samples were firmer and

presented lower electrolyte leakage during 14 d of storage at 4°C when compared to samples treated with acidic electrolyzed water. Similarly, the application of slightly acidic electrolyzed water (FCC: 20 mg L^{-1}, pH 6, ORP: +800 mV) also inhibited the growth of native microflora (total aerobic bacteria, coliforms, and yeasts and molds) on fresh-cut cilantro by approximately 1.5 log CFU g^{-1} (Hao et al., 2015)

Several studies also showed that a combination of electrolyzed water with other postharvest treatments effectively inhibited the growth of spoilage microorganisms. Hao et al. (2015) reported an additional 1 log CFU g^{-1} reduction in the native microflora (total aerobic bacteria, coliforms and yeasts and molds) of fresh-cut cilantro subjected to sequential washes of alkaline electrolyzed water (FCC: N/A, pH 11.7, ORP: –820 mV) followed by acidic electrolyzed water (FCC: 68 mg L^{-1}, pH 2.5, ORP: 1127 mV) for 5 min each. Similarly, the combination of alkaline electrolyzed water (FCC: N/A, pH 11, ORP: −800 mV) and 1% citric acid at 50°C for 3 min, significantly reduced the total microbial and yeasts and molds counts by approximately 3.7 log CFU g^{-1} in shredded carrot (Rahman et al., 2011) when compared to each treatment alone. In this study, the authors showed that mild heat treatment enhanced the effects of the sanitizing agent to kill or remove spoilage microorganisms on shredded carrot.

Although the disinfection efficiency of electrolyzed water against pathogenic and spoilage microorganisms on fresh-cut commodities has been well demonstrated in extensive literature, the decomposition of chlorine when stored under open conditions in the processing plants should be monitored from time to time to ensure the antimicrobial efficacy of electrolyzed water. Besides, the accumulation of organic matter during subsequent washing may reduce the antimicrobial activity of electrolyzed water as the available chlorine will react readily with the organic matter and deplete the concentration of HOCl.

Hydrogen peroxide

Hydrogen peroxide has been proposed as an alternative to chlorine in the food industry and can be generated by electrolytic oxidation of sulfuric acid or electrical discharge through a mixture of hydrogen, oxygen, and water vapor (FDA, 2000a). It has been classified as a GRAS substance for use in various food products (milk, dried egg, wine, starch and instant tea) as a bleaching, oxidizing and antimicrobial agent in a concentration range of 0.04–1.25%. Although the application of hydrogen peroxide in fresh or fresh-cut fruits and vegetables still awaits approval from the FDA, considerable research (Table 1) has been conducted on the use of hydrogen peroxide as an antimicrobial agent against various food spoilage and pathogenic microorganisms on blueberry (Li and Wu, 2013), lettuce (Back et al., 2014), baby spinach (Huang et al., 2012), red bell pepper, strawberry, watercress (Alexandre et al., 2012), and button mushroom (Guan et al., 2013).

Being a potent oxidant, the generation of cytotoxic oxidizing species such as hydroxyl free radicals can cause lethal damage to bacterial cells by inducing cell permeabilitization and attacking essential cell components such as lipids, proteins, and DNA (Schenk et al., 2012). It also has been proposed that hydrogen peroxide can facilitate the destruction of microorganisms by destroying biofilms and exposing the microbial cells (Martin and Maris, 2012). Besides antimicrobial activity against a wide range of microorganisms, hydrogen peroxide can be decomposed into oxygen and water by the enzyme catalase, which is naturally found in plants and hence it does not form carcinogenic residues (Alexandre et al., 2012; Ölmez & Kretzschmar, 2009; Van Haute et al., 2015).

Ukuku (2004) reported that the treatment of whole cantaloupe and honey dew melons with 2.5% hydrogen peroxide for 5 min efficiently reduced the transfer of aerobic bacteria to fresh-cut pieces by approximately 2 log CFU g^{-1}. In the study, the recovery of *Salmonella* from fresh-cut pieces after washing with 2.5% hydrogen peroxide was significantly lower than that from controls. The application of 0.9% hydrogen peroxide for 1 min also suppressed decay and browning incidence in fresh-cut Chinese water chestnut during 18 d of storage at 4°C (Peng et al., 2008). The reduction of psychrotrophic bacteria and yeasts and molds counts in fresh-cut "Galia" melon treated with hydrogen peroxide showed no significant differences with chlorine treated samples after storage for 10 d at 4°C. However, an additional reduction of approximately 0.5 log CFU g^{-1} in the growth of mesophilic and Enterobacteriaceae bacteria was achieved in hydrogen peroxide treated samples when compared to chlorine treated samples (Silveira et al., 2008).

Although hydrogen peroxide (167 mg L^{-1} for 3 min) was more effective than chlorine in reducing the native microflora (mesophilic, psychrotrophic and Enterobacteriaceae) of fresh-cut watercress, total phenolic and antioxidant content of hydrogen peroxide treated samples were reduced drastically throughout storage (Hinojosa et al., 2013). Kim et al. (2007) also reported that the total phenolic content, antioxidant capacity and ascorbic acid level of fresh-cut tomato treated with 0.4 M hydrogen peroxide for 1 min were reduced throughout storage compared to unwashed samples. Similarly, a combined treatment of 3% hydrogen peroxide for 5 min and 3.7 kJ m^{-2} UV-C for 7.5 min retained optimal microbiological stability throughout storage at 5°C. However, the treatment resulted in higher browning incidence when compared to that of the control (Schenk et al., 2012).

Considering the phytotoxic effects of hydrogen peroxide, which induced browning and degradation of nutraceutical compounds in fresh-cut produce, appropriate physical and chemical methods need to be adopted during processing to remove residual hydrogen peroxide. It has been suggested that the presence of H_2O_2 residues can be removed either by rinsing with water immediately after treatment or by combining with anti-browning agents such as ascorbic acid to avoid reactions with food constituents (Alexandre et al., 2012; Ölmez and Kretzschmar, 2009). For instance, washing fresh-cut water chestnut with water for 2 min after H_2O_2 treatment delayed the development of discoloration after 15 d of storage at 4°C (Peng et al., 2008). Meanwhile, the lack of a proper washing procedure in ready-to-eat watercress after H_2O_2 treatment may have resulted in the significant reduction of L value throughout 14 d of storage at 5°C (Hinojosa et al., 2013). Cliffe-Byrnes and O'Beirne (2008) also demonstrated that the combined treatment of 3% H_2O_2 with spray application of 4% sodium isoascorbate had resulted in lower browning indices when compared to H_2O_2 treatment alone.

Physical treatments

Ultraviolet radiation (UV)

Many studies (Table 2) have revealed that ultraviolet radiation is a promising nonthermal technology used to disinfect and decontaminate various fresh-cut fruits and vegetables. The wavelength range of ultraviolet (UV) radiation (100–400 nm) can be further subdivided into short wave UV (UV-C; 100–280 nm), medium wave UV (UV-B; 280–315 nm) and long wave UV (UV-A; 315–400 nm) (Kim et al., 2013). UV-C light in the range of 200–280 nm can be as effective as sodium hypochlorite or ozone to surface decontaminate and prolong the storage life of various fresh-cut produce (Alothman et al., 2009; Maghoumi et al., 2013; Schenk et al., 2012). The strongest micro biocidal effect of UV-C falls between 250 and 260 nm since the peak effectiveness of UV absorption by DNA is close to that range (Graça et al., 2013; Kim et al., 2013). This alternative technology has attracted attention of the fresh-cut industry since it is inexpensive to setup and operate and it does not generate chemical residues that affect the sensory attributes of fresh-cut products (Allende et al., 2006; Rico et al., 2007).

Research has suggested that UV-C doses ranging from 0.5 to 20 kJ m^{-2} can inhibit the growth of microorganisms by cross-linking aromatic amino acids at the carbon to carbon double bonds that can cause membrane depolarization, abnormal ionic flow, photochemical oxidation and pyrimidine dimer formation (Allende et al., 2006; Martínez-Hernández et al., 2015b). Alteration of the DNA helix by distortion of the sugar phosphate backbone may inhibit microbial DNA replication and transcription causing cell death and mutation (Artés et al., 2009; Kim et al., 2013). For example, the population of *E. coli, L. innocua*, and *S. enterica* in artificially inoculated fresh-cut apple was reduced by approximately 1.5–1.9 log CFU g^{-1} following UV irradiation at 1.0 kJ m^{-2} (Graça et al., 2013). The counts of the three bacteria strains were significantly lower in irradiated fruit than in control fruit after 7 and 15 d of storage at 4°C and the reduction was comparable to that in sodium hypochlorite treated fresh-cut apple. Similarly, when compared to unirradiated samples, 7.5 kJ m^{-2} of UV-C radiation significantly reduced the population of *E. coli* and *S. enterica* on inoculated fresh-cut kalian-hybrid broccoli by 1.3 and 2.1 log CFU g^{-1}, respectively (Martínez-Hernández et al., 2015b). Approximately a 1–2 log CFU g^{-1} reduction in the population of native microflora also has been reported in UV-C irradiated fresh-cut pomegranate arils (Maghoumi et al., 2013) and watermelon (Artés-Hernández et al., 2010).

Although the application of UV-C doses from 4.54 to 11.35 kJ m^{-2} effectively inhibited the growth of mesophilic and enterobacteria in fresh-cut spinach, the population of psychrophilic bacteria was not reduced during storage (Artés-Hernández et al., 2009). Allende et al. (2006) also showed that UV-C radiation was ineffective in inhibiting the growth of yeasts in fresh-cut lettuce as the population for all samples was beyond the microbial recommended limit after storage for 5 d at 5°C. Similarly, the population of spoilage microorganisms in UV-C radiated fresh-cut pomegranate arils showed no significant differences with unirradiated samples and reached the maximum microbial limit suggested by the Spanish Legislation following 13 d of storage at 5°C (López-Rubira et al., 2005). Inconsistent results obtained in various UV-C treated fresh-cut produce may be due to different composition of produce and site of microorganism attachment on the product (Allende et al., 2006; Tomás-Callejas et al., 2012). It has been suggested that UV-C does not penetrate the produce tissues, so bacteria that are attached in cracks and crevices of fresh-cut produce may not be exposed directly to UV-C radiation (Graça et al., 2013).

In addition to lethal germicidal effects, it has been proposed that UV-C radiation can induce biological stress and the development of defense mechanisms against microorganisms and senescence process in plant tissues (Alothman et al., 2009; González-Aguilar et al., 2007). These inducible effects are often accompanied by the accumulation of secondary metabolites with increased antioxidant activity and alteration in the activity of degradative enzymes. For instance, the total phenol content and antioxidant activity of UV-C irradiated fresh-cut Tatsoi baby leaves were increased by 23.7% and 8.5%, respectively, after storage for 4 d at 5°C (Tomás-Callejas et al., 2012). The antioxidant capacity has been reported to increase in fresh-cut mango (González-Aguilar et al., 2007), carrot (Alegria et al., 2012), pineapple, guava, and banana (Alothman et al., 2009). Interestingly, the activity of degradative enzymes (PPO, POD, PME, and PG) in "Galia" melon treated with 4.8 kJ m^{-2} of UV-C radiation was significantly lower than in unirradiated samples throughout storage (Chisari et al., 2011). The reduction of these enzymes in UV-C treated melon coincided with significantly higher firmness and lower color changes when compared to unirradiated samples following 10 d of storage at 5°C.

To date, extensive researches have shown the potential application of ultraviolet radiation as a food disinfection technique due to its strong antimicrobial efficacy against the growth of spoilage and pathogenic microorganisms. Depending on the dosage, exposure time and raw materials used, ultraviolet radiation can also be used as an elicitor to enhance plant defense mechanisms by elucidating the production of secondary metabolites and increasing the total antioxidant capacity of fresh-cut products. However, just like other emerging technologies, the standardization on the ultraviolet radiation parameters (UV light fluence and treatment time) has yet to be carried out at the industrial scale to further validate the concept and its practicability in the fresh-cut industry. Also, the biochemical pathway for the production of secondary metabolites in irradiated fresh-cut produce still remains obscure and requires further exploration in future studies.

High pressure processing

High hydrostatic pressure is a non-thermal technology that is increasingly used in the food industry to inactivate a broad spectrum of foodborne pathogens and food deteriorative enzymes with minimal effect on the overall quality, nutraceutical properties or flavor of liquid and solid foods (Jung et al., 2013; Ortega et al., 2013). Pressurization of food products can be carried out using pressures between 100 and 800 MPa at process temperatures ranging from 0 to 100°C with a recommended practical exposure time of up to 20 min (FDA, 2000b; Maitland et al., 2011). Studies have suggested that the application of pressure ranges from 300 to 600 MPa can effectively inhibit the growth of most microorganisms and maintain the

Table 2. Physical treatments and their effects on fresh-cut fruits and vegetables.

Treatment	Parameters	Fresh-cut fruits/vegetables	Results	References
Ultraviolet radiation	UV-B dose: 3.1 kJ m^{-2} Storage: 10 d, 5°C	Iceberg lettuce	A combination of wounding and UV-B exposure was found to increase the total soluble phenolic content in iceberg lettuce and parsnip by 1.2 and 2.3 times.	Du et al., 2014
	UV-C dose: 7.5 kJ m^{-2} Storage: 14 d, 5°C	Kailan-hybrid broccoli	The population of *E. coli* and *S. Enteritidis* inoculated on samples were reduced significantly by 1.3 and 2.1 log CFU g^{-1}.	Martínez-Hernandez et al., 2015b
	UV-C dose: 8.0 kJ m^{-2} Storage: 21 d, 0°C	Broccoli	Combination of hot air at 48°C and UV-C treatment resulted in higher chlorophyll content and maintenance of organoleptic properties.	Lemoine et al., 2010
	UV-C dose: 1.0 kJ m^{-2} Storage: 15 d, 4°C	Apple	A 2 log cycle reduction in the population of *E. coli, S. enterica*, and *L. innocua* was observed in UV-C irradiated samples.	Graça et al., 2013
	UV-C dose: 20.40 kJ m^{-2} Storage: 7 d, 4°C	Lettuce	The population of *E. coli, S. Typhimurium* and L. *innocua* inoculated on samples was reduced by 1.9, 2.7, and 2.2 log CFU g^{-1}, respectively.	Kim et al., 2013
	UV-C dose:4.54 kJ m^{-2} Storage: 14 d, 5°C	Pomegranate arils	UV-C treatment significantly reduced the growth of mesophiles and yeasts and molds during storage.	Maghoumi et al., 2013
	UV-C dose: 0.78 ± 0.36 kJ m^{-2} Storage: 10 d, 5°C	Carrot	UV-C treatment was found to inhibit the activity of POD and increase the carotenoid content by 3-fold during storage.	Alegria et al., 2012
Ultraviolet radiation	UV-C dose: 3.7 kJ m^{-2} Storage: 6 d, 5 ± 1°C	Pear	A 2 log cycle reduction of *E. coli, L. innocua* and *Zygosaccharomyces bailii* inoculated on pear discs was observed after UV-C treatment.	Schenk et al., 2012
	UV-C dose: 4.54 kJ m^{-2} Storage: 11 d, 5°C	Tatsoibaby leaves	A 1 log cycle reduction in the population of mesophiles was observed in UV-C treated samples during storage.	Tomás-Callejas et al., 2012
	UV-C dose: 4.8 kJ m^{-2} Storage: 10 d, 5°C	Melon	The activity of deteriorative enzymes (POD, PPO, PME, and PG) was significantly inhibited after UV-C treatment. UV-C irradiated samples were firmer (approximately 7–12%) than control.	Chisari et al., 2011
	UV-C dose: 1.2 kJ m^{-2} Storage: 14 d, 6°C	Melon	UV-C treatment improved sensorial attributes of the samples and reduced the total viable counts and Enterobacteriaceae population by 2 log CFU g^{-1}.	Manzocco et al., 2011
	UV-C dose: 1.6 kJ m^{-2} Storage: 11 d, 5°C	Watermelon	UV-C treatment resulted in a 2 log cycle reduction in the population of mesophiles, psychrotroph, and Enterobacteriaceae and no decay symptoms were observed during storage.	Artés-Hernández et al., 2010
	UV-C dose: 2.2 J m^{-2} Storage: N/A	Pineapple Banana Guava	UV-C treatment enhanced the total antioxidant capacity of tropical fruits as measured by DPPH and FRAP.	Alothman et al., 2009
	UV-C dose: Irradiated for 10 min Storage: 15 d, 5°C	Mangoes	The activity of antioxidant enzymes (PAL and LOX) in UV-C irradiated samples was up-regulated and hence conferred better resistance against fungal infection.	González-Aguilar et al., 2007
	UV-C dose: 2.27 kJ m^{-2} Storage: 15 d, 5°C	Pomegranate arils	Initial loads of spoilage microorganisms were reduced in samples after UV-C treatment. However, the antimicrobial effect of UV-C was not prolonged as shown by rapid growth of spoilage microorganisms during storage.	López-Rubira et al., 2005
High pressure	Pressure: 500 MPa, 10 min Storage: N/A	Bean sprout Carrot Cucumber Spinach Mushroom Korean radish	The population of *L. monocytogenes, Staphylococcus aureus* and *Salmonella Typhimurium* inoculated in ready-to-eat vegetables was significantly inhibited.	Jung et al., 2014
	Pressure: 600 MPa, 1 min Storage: N/A	Mango	The growth of aerobic bacteria and yeasts and molds was inhibited to a level below the detection limit.	Liu et al., 2013
	High pressure CO_2: 12 MPa, 1 min Storage: 28 d, 4°C	Carrot	A 5 log cycle of reduction on the growth of mesophiles and lactic acid bacteria was achieved. However, treatment resulted in lower ascorbic acid content and total antioxidant capacity when compared to control.	Spilimbergo et al., 2013

(*Continued on next page*)

Table 2. (Continued).

Treatment	Parameters	Fresh-cut fruits/vegetables	Results	References
High pressure	Pressure: 600 MPa, 6 min Storage: N/A	Avocado	Contradictory findings were observed on the enzymatic activity of PPO and POD. The activity of POD was inhibited but higher PPO activity was observed. Cell wall structure and internal cytoplasmic structure of the cell were disrupted in treated samples.	Woolf et al., 2013
	High pressure argon + xenon: 1.8 MPa (argon: xenon = 2:9 partial pressure), 60 min Storage: 4 d, 4°C	Apple Pineapple	Treatment resulted in better resistance against the growth of *E. coli* and *S. cerevisiae* and associated with higher phenolic contents when compare to control.	Wu et al., 2013
	High pressure argon: 1.8 MPa, 60 min Storage: 20 d, 4°C	Pineapple	Growth of spoilage microorganisms was inhibited during storage and the storage life of treated pineapple was extended by 6 d.	Wu et al., 2012
	High pressure CO_2: 5 MPa, 20 min Storage: N/A	Carrot	Treatment effectively inhibited the growth of aerobic bacteria and yeasts and molds. However, significantly higher relative electrolyte leakage was observed in treated samples when compared to control and indicated the treatment caused cell damage.	Bi et al., 2011
	High pressure CO_2: 550 MPa, 2 min Storage: N/A	Tomato	*In vitro* studies showed that treatment resulted in a 6 log cycle reduction in the population of four *Salmonella enterica* serovars (Newport, Braenderup, Javiana and Anatum) in broth culture. Counts of *Salmonella enterica* serovars Braenderup inoculated on diced tomato were reduced by 3.7 log CFU g^{-1}.	Maitland et al., 2011
Ultrasound	Bath: 37 kHz; 25 & 29 W; 10 & 15 min	Fresh-cut pineapple	Ultrasound treatment inhibited activities of PPO and PPP and enhanced activity of PAL, phenolic contents, and antioxidant capacity during cold storage	Yeoh and Ali, 2017
	Bath: 40 kHz; 200 W; 5 min Storage: 12 d, 3°C	Fresh-cut potato	Ultrasound treatment for a duration of 5 min inhibited the activity of PPO and no visible browning was observed.	Amaral et al., 2015
	Bath: 40 kHz; 180 W; 7.5 min Heat shock: 50°C; 3 min Citric acid: 1.5% (w/v); 3 min Storage: 10 d, 5°C	Fresh-cut broccoli	Ultrasound in combination with citric acid and thermal treatment was found to extend the storage life of fresh-cut broccoli by maintaining the chlorophyll content, nutritional quality and inhibiting the growth of microorganisms.	Ansorena et al., 2014
	Bath: 20 kHz; 130 W; 10 min CaO: 2% (w/v) Storage: N/A	Apple slices	The population of *E. coli* O157:H7, *L. monocytogenes* and *S. typhimurium* artificially inoculated on apple slices was reduced by 1.45, 2.67 and 2.23 $\log_{10}$ CFU g^{-1}.	Yoon et al., 2013
	Bath: 40 kHz; 400 W; 65°C; 15 −17 min Calcium propionate: 2% (w/v) Storage: 7 d, 10°C	Fresh-cut celery	Combination of ultrasound, calcium propionate and thermal treatment significantly inhibited the population of *E. coli* O157:H7 and *S. Typhimurium* by 7 and 5 $\log_{10}$ CFU g^{-1}.	Kwak et al., 2011
	Bath: 45 kHz; 1 min Storage: N/A	Shredded carrot	Combination of heat and ultrasound treatment resulted in the highest reduction of mesophiles (1.7 $\log_{10}$ CFU g^{-1}) and yeasts and molds (1.1 $\log_{10}$ CFU g^{-1})counts	Alegria et al., 2009

overall quality of food products (Maitland et al., 2011; Ortega et al., 2013).

Chemical changes in high hydrostatic pressurized food products are minimal as the covalent bonds are not broken during treatment (Liu et al., 2013). Instead, weaker bonds such as Van der Waals forces, electrostatic interactions and hydrogen bridges are easily affected by the applied pressure (Mújica-Paz et al., 2011). Another advantage of high hydrostatic pressure processing is that pressure at a given position and time during treatment can be distributed instantaneously and uniformly on food products irrespective of different food composition, size and shape (FDA, 2000b; Rawson et al., 2011). Many studies have shown that high hydrostatic pressure processing can be efficiently used to preserve and enhance the microbial stability of various food products such as fruit puree (Guerrero-Beltran & Barbosa-Cánovas, 2004; Krebbers et al., 2003), fruit juices (Alphas and Bozoglu, 2000; Lavinas et al., 2008), fresh commodities (Jung et al., 2013; Maitland et al., 2011; Ortega et al., 2013) and meat (Moerman, 2005).

Germicidal effects of high hydrostatic pressure against various pathogenic bacteria have been reported in several fresh-cut fruits and vegetables. For example, the growth of *S. enterica serovar* Braenderup inoculated in diced tomato was reduced significantly by 3.65 log CFU g^{-1} following exposure to high hydrostatic pressure treatment at 550 MPa for 2 min (Maitland et al., 2011). Upon pressurization at 500 MPa with a holding time for 10 min, the number of *L. monocytogenes, S. aureus*, and *S. typhimurium* inoculated in various fresh-cut vegetables were inhibited to below the detection limit (Jung et al., 2014).

However, irreversible changes in the structure of important macromolecules such as deoxyribonucleic acid (DNA) and proteins during high hydrostatic pressure processing can induce permeabilization of cytoplasmic membranes, leading to vegetative cell damage (Mújica-Paz et al., 2011; Ross et al., 2003). It is worth noting that high pressure causes tighter packing of the acyl chains within the membrane's phospholipid bilayers and reduces cross-sectional area per phospholipid molecules which can promote the permeabilization of cell membrane (Mañas and Pagán, 2005; Ross et al., 2003). Disruption of the cell membrane often results in extensive leakage of solutes and loss of osmotic responsiveness and hence cell death.

Recently, a novel technique involving the combination of high pressure and an inert gas treatment has been reported to enhance the storage life and inhibit the growth of microorganisms in various fresh-cut produce (Table 2). For instance, the shelf life of fresh-cut pineapple treated with pressurized argon at 1.8 MPa for 60 min was extended by 6 d as the proliferation of native microflora was slowed down throughout storage when compared to that of control (Wu et al., 2012). Wu et al. (2013) also reported that the combination of pressurized argon and xenon significantly inhibited the growth of *E. coli* and *S. cerevisiae* inoculated in fresh-cut apple and pineapple throughout 7 d of storage at 10°C. The formation of inert gas hydrate under high pressure and low temperature in fresh-cut fruits and vegetables can inhibit the intracellular water activity and restrain metabolism and bioactivity in microorganisms (Wu et al., 2012).

Although current studies have demonstrated that the use of high pressure processing can achieve satisfactory microbial reduction and inactivation of deteriorative enzymes in various food products, experimental conditions such as pressure applied and exposure time may have resulted in different findings on the organoleptic and nutritional properties of fresh-cut produce. Particularly, the texture and microscopic study on the structure of fresh-cut fruits and vegetables should be investigated further as the application of high pressure could possibly introduce more mechanical damage to the cut produce and affect the firmness of end products. Currently, the application of this technology may not be economically feasible due to the high initial capital expenditure.

Ultrasound

Ultrasound technology is a form of vibrational energy in the frequency range of 20–100 kHz, which is beyond the threshold of human hearing (Soria and Villamiel, 2010). Based on the amount of energy used, which is often measured by sound power (W), intensity (W m^{-2}), and energy intensity (W s^{-1} m^{-3}), the application of ultrasound in various industries can be categorized into low and high intensity ultrasound (São José et al., 2014). Low energy ultrasound is characterized by power intensity <1 W cm^{-2} at high frequency (>1 MHz) and is commonly used in medical diagnostics (Awad et al., 2012; Soria and Villamiel, 2010). In the food industry, small amplitude sound waves are used to conduct non-destructive analyses and access physicochemical properties of food materials such as their composition, viscosity and structure (Kentish and Feng, 2014). Contrarily, high power ultrasound with power intensity ranging from 10 to 1000 W cm^{-2} at low frequency (16–100 kHz) has wide application in food processing, preservation and safety (Awad et al., 2012; Soria and Villamiel, 2010). High amplitude sound waves can alter the properties of food physically or chemically. The disruptive properties of high power ultrasound have been applied in the extraction of bioactive compounds, the inactivation of microbial growth and enzymes activity, emulsification, and surface cleaning (O'Donnell et al., 2010; Patist and Bates, 2008; Piyasena et al., 2003).

During the sonication process, longitudinal waves are created when sound energy passes through liquid medium thereby creating regions of alternating compression and rare fraction. These regions of pressure change cause cavitation to occur and bubbles are formed from gas nuclei existing within the fluid. These bubbles have a large surface area during the expansion cycle when the pressure is at a minimum, which increases the diffusion of gas and causes the bubbles to expand (Patist and Bates, 2008; Piyasena et al., 2003; Soria and Villamiel, 2010). Stable changes in the size of bubbles during the oscillation of ultrasonic waves can result in stable cavitation and generate acoustic micro-agitation on the medium (Cárcel et al., 2012; Kentish and Feng, 2014). However, these bubbles become unstable and collapse violently when the ultrasonic energy provided resonates with the fluctuation of the bubble wall (Sango et al., 2014). The condition within these implosions of bubbles leads to energy accumulation in hot spots and generates high temperatures (5000 K) and pressures (1000 atm), which in turn produce very high shear energy waves and turbulence in the cavitation zone (Bilek and Turantaş, 2013; Chandrapala et al., 2012; Sango et al., 2014).

Disruption of bacterial cellular structure and subsequent leakage of cellular components due to high pressure and temperature can lead to bacterial cell lysis (Chemat et al., 2011; São José et al., 2014; Soria and Villamiel, 2010). Chandrapala et al. (2012) suggested that the hydrophobic surface of microorganisms can also promote the collapse of cavitation bubbles and lead to severe damage on the cell wall. The presence of multilayered hydrophobic cuticles and uneven surfaces of some fresh or fresh-cut fruits and vegetables may provide some protection for the bacterial cells and inhibit effective sanitizing of the fresh produce (São José et al., 2014). Acoustic microstreaming associated with strong shear force, which is produced during the oscillation of ultrasound waves and subsequent collapse of cavitation bubbles, can be used to remove microorganisms on the surface cracks and crevices of fresh produce (Kentish and Feng, 2014; Soria and Villamiel, 2010). The shear force can break the cell wall and membrane of microorganism up to the point of cell lysis (Bilek and Turantaş, 2013; São José et al., 2014).

Another important effect is that water molecules can be broken generating highly reactive free radicals that may react with and modify other molecules (Awad et al., 2012; Soria and Villamiel, 2010). Free radicals such as hydroxyl radicals (OH-) can react with the sugar phosphate backbone of DNA by removing hydrogen atoms from the sugars (Bilek and Turantaş, 2013). The double stranded microbial DNA can be broken through the scission of the phosphate ester bond (Chandrapala et al., 2012; Mañas and Pagán, 2005).

In recent years, ultrasound frequency ranges from 20 to 45 kHz and treatment times from 1 to 10 min have been tested

in the washing procedures of intact and fresh-cut fruits and vegetables (Table 2). The combination of different ultrasound parameters such as power, temperature and time can result in 0.5–2.0 log microbial reductions (Bilek and Turantaş, 2013). In most of these studies, fresh produce such as strawberries and lettuce were used to study the decontamination efficiency of ultrasound. For example, Cao et al. (2010) reported that the decay incidence of ultrasonicated strawberry (40 kHz, 350 W, 10 min) was significantly reduced by 43.7% when compared to that of control fruit. Based on the results obtained, the authors showed that frequency is one of the parameters affecting the efficacy of ultrasound. São José et al. (2014) suggested that the size of bubbles formed during ultrasonication is inversely proportional to the acoustic frequency. Formation of larger bubbles at lower frequency of ultrasonic waves can result in higher localized pressure and temperature due to a greater incidence of collapse events of cavitation bubbles (Kentish and Feng, 2014). Birmpa et al. (2013) also showed that ultrasonication (37 kHz, 30 W) for 45 min resulted in a significant reduction of more than 2 log in the population of *E. coli, Listeria innocua, Salmonella rnteritidis*, and *Staphylococcus aureus* inoculated on lettuce and strawberry.

Similarly, the counts of *Salmonella typhimirium* inoculated on fresh-cut iceberg lettuce were reduced by 1.6 log CFU g^{-1} following ultrasonication (32–40 kHz, 10 W L^{-1}) for 10 min and the results obtained were comparable to those observed with chlorine treatment, which decreased by 1.7 log CFU g^{-1} (Seymour et al., 2002). Alegria et al. (2009) also reported that an ultrasound pretreatment (45 kHz) for 1 min prior to shredding the carrots effectively reduced the population of aerobic bacteria and yeasts and molds by 1.3 and 0.9 log CFU g^{-1}, respectively.

Some studies have revealed that the combination of ultrasound with other chemical sanitizers such as organic acids, chlorine dioxide, calcium propionate and salicylic acid may result in a higher reduction of microbial populations than ultrasound alone. For instance, an additional 2 log reduction of the growth of *E. coli* O157:H7 and *L. monocytogenes* inoculated on apple slices was observed following combined treatment of calcium oxide (2% CaO) and ultrasound (20 kHz, 130 W, 10 min) (Yoon et al., 2013). Similarly, Kwak et al. (2011) showed that the antimicrobial efficiency of ultrasound (40 kHz, 400 W, 15–17 min) against *E. coli* O157:H7 and *S. typhimurium* inoculated on fresh-cut lettuce was improved when combined with 2% calcium propionate and heat (65°C) treatments.

Besides antimicrobial effects, ultrasound (40 kHz, 200 W, 5 min) treatment was also found to prevent browning in fresh-cut potato by inhibiting the activity of PPO (Amaral et al., 2015). Recently, Yeoh and Ali (2017) reported the effect of ultrasound treatment on the phenolic metabolism and antioxidant capacity of fresh-cut pineapple during cold storage. They opined that treatments at 25 and 29 W significantly increase the activity of phenylalanine ammonia lyase by 2.0- and 1.9-folds in relation to control samples. Moreover, the activity of browning causing enzymes (polyphenol oxidase and polyphenol peroxidase) was significantly decreased in fresh-cut pineapple following the ultrasound treatment.

It has been suggested that acoustic streaming, which is associated with high shear forces, can disrupt the hydrogen bonding and Van der Waals forces of polypeptide chains and result in the conformational change of the secondary and tertiary structure of proteins (Chandrapala et al., 2012). Binding of hydroxyl and hydrogen free radicals generated during sonication with some of the amino acid residues that are responsible for substrate binding, stability and catalytic activity of enzymes can result in the alteration of biological activity (Kentish and Feng, 2014; São José et al., 2014).

Although studies have showed that ultrasound can effectively inhibit the growth of microorganisms and the activity of degradative enzymes, its effects on the quality and physiological changes in fresh produce are not well documented. For instance, Birmpa et al. (2013) observed that ultrasound treatment (37 kHz, 30 W L^{-1}) applied for 46 and 60 min resulted in changes in the color (ΔE) of lettuce and strawberry. Gabaldón-Leyva et al. (2007) demonstrated that the physical forces generated by ultrasound treatment at 45 kHz for 30 min negatively affected the textural properties of bell peppers by damaging the cell wall structure.

Meanwhile, Sagong et al. (2011) showed that the changes in the L, a^*, and b^* values of fresh lettuce treated at 40 kHz of ultrasound and power of 30 W L^{-1} for 5 min were comparable to those of the control following 7 d of storage at 4°C. The application of 30 W of ultrasound for 5–10 min also resulted in increased firmness in strawberry following 4 weeks of storage at 4°C (Aday et al., 2013). Cao et al. (2010) reported that strawberry treated at 250 W of ultrasonic wave for 10 min retained 74.7% of initial firmness at the end of storage period. Higher level of firmness was also reported in ultrasound treated plum fruit (Chen and Zhu, 2011) and white mushroom (Lagnika et al., 2012) than control samples. Inconsistent results obtained in the physicochemical properties of various ultrasound treated fruits and vegetables in these experiment may be due to the differences in frequency, treatment time and power output.

Although the antimicrobial efficacy of ultrasound against spoilage and pathogenic microorganisms in fresh produce has been well elucidated, there is insufficient information about the effectiveness of ultrasound treatment to enhance the storage life and reduce the microbial population of fresh-cut fruits and vegetables. Besides, it has been proposed that the formation of free radicals during sonolysis of water and generation of high shear forces due to the implosion of cavitation bubbles can impose oxidative stress and thus activate plant defense responses. Several studies on the application of ultrasound treatment have been found to induce antioxidants those could contribute antimicrobial properties in strawberry (Cao et al., 2010) and plum fruits (Chen and Zhu, 2011). However, the possible biological stimuli and signals that may activate and control the elicitation of bioactive compounds in ultrasound treated fresh-cut fruits and vegetables remain unclear. Additional studies on the organoleptic properties and quality of fresh-cut produce have to be further investigated, especially in the absence of protective epidermis layers due to various degrees of processing which make the minimally processed fruits and vegetables more vulnerable to biotic and abiotic stresses. The ultrasound could be a good alternative to other preservative techniques that are currently employed in the fresh-cut industry to inactivate a broad spectrum of microorganisms. It is also worth noting that any novel decontamination

technology including ultrasound treatment has to be scaled up to determine the process conditions for industrial application as the cavitation efficiency will be affected by the presence of organic matter, water hardness and type of dissolved gases in a large plant environment. Also, a long term solution has to be delivered to address the issue related to the increase in water bath temperature during sonication.

Edible coating

Biodegradable and environmental friendly materials that are used to wrap and extend the shelf life of food products, form the basic idea of edible coatings (Azarakhsh et al., 2014a; Mantilla et al., 2013; Moreira et al., 2011). Edible coatings, which utilize proteins, lipids and polysaccharides as their raw materials are a promising alternative technology in the fresh-cut industry to meet challenges related to safety, quality and economic production cost (Ghidelli et al., 2014; Leceta et al., 2015).

The formation of semipermeable barriers by edible coatings can reduce the deleterious effects of minimal processing by slowing down moisture and solute migration, gas exchange, respiration rates, flavor loss and physiological disorders development in fresh-cut fruits and vegetables (Benitez et al., 2014; Maya-Meraz et al., 2014; Robles-Sánchez et al., 2013). For example, Azarakhsh et al. (2014a) reported that the application of a 0.56% gellan based edible coating was able to reduce respiration rate and color change, and maintain firmness and

Table 3. Edible coatings and their effects on various fresh-cut fruits and vegetables.

Treatment	Parameters	Fresh-cut fruits/ vegetables	Results	References
Edible coating	Coating: 1% (w/v) chitosan Method: Dipping or spraying for 30 s Storage: 15 d, 4°C	Baby carrot	Results demonstrated that chitosan inhibited the growth of coliforms and *S. aureus* significantly during storage. However, a low reduction in the total viable, yeasts and molds, *Pseudomonas* and *Bacillus cereus* counts was observed in this study.	Leceta et al., 2015
	Coating: 1.29% (w/v) sodium alginate + 0.3% (w/v) lemongrass oil Method: Dipping for 5 min Storage: 16 d, 10°C	Pineapple	Storage life of coated samples was extended up to day 12 of storage as the growth of spoilage microorganisms was inhibited when compared to control which only last up to day 8 of storage.	Azarakhsh et al., 2014b
	Coating: 0.56% (w/v) gellan gum Method: Dipping for 2 min Storage: 16 d, 5°C	Pineapple	Gellan based coating was ineffective to slow down the proliferation of spoilage microorganisms. However, coated samples displayed better retention of firmness and color in comparison to control.	Azarakhsh et al., 2014a
	Multilayered coating: 1% (w/v) alginate + 2% (w/v) trans-cinnaldehyde + 2% (w/v) pectin Method: Dipping for 2 min in each solution Storage: 15 d, 4°C	Pineapple	The formulation of coating solution significantly reduced the population of aerobic microorganisms, psychrotrophs, and yeasts and molds by 2.5, 1.1 and 1.8 log CFU g^{-1} after 15 d of storage.	Mantilla et al., 2013
Edible coating	Coating: 2% (w/v) cassava starch + 0.5% (w/v) ascorbic acid + 0.5% (w/v) citric acid Method: Dipping for 2 min Storage: 12 d, 5°C	Pineapple	Coating did not significantly reduce the yeast and mold counts after 12 d of storage. However, juice leakage and weight loss was significantly lower than those of control samples throughout storage.	Bierhals et al., 2011
	Coating: 2% (w/v) chitosan + bioactive compounds Method: Dipping for 3 min Storage: 7 d, 5°C	Broccoli	The combination of coating solution with bioactive compounds effectively reduced the spoilage and pathogenic microorganisms.	Alvarez et al., 2013
	Coating: 2% (w/v) chitosan Method: Dipping for 2 min Storage: 20 d, 5°C	Broccoli	Population of spoilage and pathogenic microorganisms and yellowing symptoms were inhibited throughout storage.	Moreira et al., 2011
	Coating: 5% (v/v) aloe vera Method: Dipping for 10 min Storage: 12 d, 4°C	Kiwi	The reduction of mesophiles and yeasts and molds counts was less than 0.5 log CFU g^{-1} throughout storage. However, the coated samples displayed better quality than control during storage.	Benítez et al., 2013
Edible coating	Multilayered coating: 2% (w/v) chitosan + 2% (w/v) trans-cinnaldehyde + 2% (w/v) pectin + 2% calcium chloride Method: Dipping for 2 min in each solution Storage: 15 d, 4°C	Papaya	Coated fruits had lower aerobic, psychrotrophic and yeasts and molds growth without affecting the fruit's flavors during cold storage.	Brasil et al., 2012
	Coating: 2% (w/v) chitosan Method: Dipping for 2 min Storage: 14d, 5°C	Papaya	Mesophiles and yeasts and molds counts of chitosan coated fruits were significantly reduced by 4.5 and 3.9 log CFU g^{-1} at the end of storage day. Activity of cell wall degrading enzymes such as polygalacturonase and pectin methyl esterase was also reduced in coated fruits.	González-Aguilar et al., 2009
	Coating: alginate + isoleucine Method: Dipping for 3 s Storage: 21 d, 3°C	Apple	Addition of isoleucine in the coating solution increased the production of aroma volatile compounds in coated samples.	Maya-Meraz et al., 2014
	Coating: 2% (w/v) sodium alginate Method: Dipping for 2 min Storage: 15 d, 5°C	Melon	The coating solution was ineffective to inhibit the proliferation of spoilage microorganisms during storage. However, coated fruits maintained better firmness in comparison to control.	Oms-Oliu et al., 2008

sensory characteristics of fresh-cut pineapple throughout 16 d of storage at 5°C. These authors also reported that the formulation of the gellan coating showed no antimicrobial effects against the native microflora of fresh-cut pineapple. Similarly, the growth of aerobic psychrophilic bacteria and yeasts and molds was not inhibited during storage in polysaccharides-based (gellan, alginate, and pectin) edible coated fresh-cut melon, but the coating prevented desiccation and maintained fruit firmness (Oms-Oliu et al., 2008). The gellan-based edible coatings were able to maintain high levels of vitamin C in fresh-cut melon throughout storage in comparison to control fruit. Recently, the application of a 5% aloe vera dip for 15 min successfully reduced the respiration rate and maintained the firmness and green pulp of fresh-cut kiwifruit during 11 d of storage at 4°C, although the growth of mesophiles and yeasts and molds was only reduced by 0.21–0.99 log CFU g^{-1}(Benítez et al., 2013).

Some studies (Table 3) also have showed that selected coating materials such as chitosan, which has antibacterial properties, can improve food appearance and inhibit the growth of pathogenic and spoilage microorganisms (Alvarez et al., 2013). González-Aguilar et al. (2009) reported that the population of mesophilic bacteria and yeasts and molds was reduced by 2.4 and 2.3 log CFU g^{-1}, respectively, in chitosan coated (2% medium molecular weight for 2 min) fresh-cut papaya after storage for 7 d at 5°C. Changes in firmness and color and polygalacturonase activity of chitosan-treated papaya were reduced when compared to control fruit samples. Similarly, the growth of native microflora (mesophilic, psychrotrophic, coliforms and yeasts and molds)in chitosan dipped (2% medium molecular weight chitosan for 3 min) fresh-cut broccoli was effectively inhibited by 0.8–2.5 log CFU g^{-1} throughout 20 d of storage at 5°C (Moreira et al., 2011).

Considering the potential of polysaccharide based edible coatings to form an effective semi protective barrier, it was suggested that the incorporation of different active agents such as natural antioxidants and antimicrobial agents could further enhance polysaccharide formulations (Mantilla et al., 2013; Oms-Oliu et al., 2008). Maya-Meraz et al. (2014) reported that the addition of isoleucine to an alginate coating significantly enhanced the production of 2 methyl-1-butanol and 2-methyl butyl acetate in fresh-cut apples, which are the main volatile compounds that contribute to apple flavor. The incorporation of 0.3% lemongrass oil in a 1.29% alginate coating solution significantly reduced total plate and yeasts and molds counts while maintaining firmness, color and sensory attributes of fresh-cut pineapple (Azarakhsh et al., 2014b). These studies have shown that the incorporation of natural compounds in edible coatings conferred better resistance against spoilage microorganisms and extended the storage life of fresh-cut products. However, the characterization and determination of the safe lethal limits for humans' consumption on these plant extracts and other natural resources are essential to gain approval of these substances as food additives.

In recent years, mounting evidences have demonstrated the potential of edible coatings as a green and sustainable alternative to ensure food safety and improve the organoleptic properties and quality of fresh-cut fruits and vegetables. Although GRAS substances such as glycerol, calcium chloride, acetic acid and ascorbic acid are added in the formulation of edible coatings within the permissible concentration, the incorporation of these chemical substances may affect the taste and flavor of the end products and hinder consumers' acceptance towards this alternative.

Conclusions

Decontamination and washing of fresh-cut fruits and vegetables are important procedures to remove cell exudates that promote the growth of spoilage and pathogenic microorganisms and limit storage life. Currently, chlorine is typically used by the industry as the sanitizer of choice due to its reliable availability, efficacy and low cost. However, maintaining constant free chlorine concentration in the wash water requires periodic monitoring to prevent chlorine off-gas and formation of carcinogenic compounds. Alternatives to chlorine discussed in this review have showed similar or even higher reduction in the population of spoilage and pathogenic microorganisms in various fresh-cut produce without compromising their quality during storage. However, most of the applications of these postharvest technologies have only been tested at the laboratory scale, which cannot relay realistic information to the fresh-cut industry. Additionally, different experimental design and parameters that are being adopted in each of the mentioned postharvest technologies have resulted in contradictory results in various fresh-cut produce. Considering the needs of the industry to identify alternatives that could be used to extend the storage life of a broad spectrum of fresh-cut produce, further research should be conducted at a commercial scale by using published results as a guide to establish experimental parameters. Much of current research has been driven by the needs of consumers for synthetic chemical-free products as they are aware of health concerns with food preservatives. However, little is known about consumer acceptance of these novel postharvest technologies, which could inhibit their application by the fresh-cut industry. Research to assess the acceptance of these alternative treatments by consumers should be conducted. Considering the unknown acceptance of novel postharvest technologies by consumers and the significant number of research papers that have been published each year, this exploratory approach could provide insight into consumer needs and generate research ideas for postharvest treatments that can be potentially funded and applied in the fresh-cut industry.

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