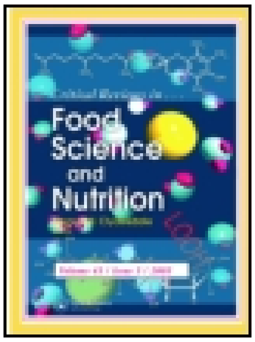

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REVIEW

Quality of fresh and fresh-cut produce impacted by nonthermal physical technologies intended to enhance microbial safety

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ABSTRACT
Nonthermal physical intervention technologies are able to reduce populations of foodborne pathogens on/in fresh produce. As highly perishable and living organisms, fresh produce is inherently sensitive to any physical or chemical treatment in terms of quality damage. The aims of the present review are to summarize current knowledge on non-thermal technologies (ionizing radiation, UV and pulsed light, ultrasound, high hydrostatic pressure, and cold plasma) with an emphasis on their impact on quality of fresh produce and to discuss advantages, disadvantages, and considerations for the commercialization of each technology. The impact of nonthermal physical technologies on fresh produce quality is related to pathogen inactivation mechanisms of each individual technology, and the nature and intensity of changes in quality due to the technologies depend on the treatment intensity/time and other processing conditions. Common symptoms of quality deterioration due to nonthermal processing include tissue softening, browning, and loss of nutrients. In general, there is a lack of systematic assessment, particularly sensory evaluations using taste panels of the product quality after treatments. For emerging technologies, such as cold plasma, more studies are necessary in order to assess quality changes during post-treatment storage at relevant temperatures. Quality of fresh produce must be carefully investigated to facilitate the commercialization of technologies.

KEYWORDS
Ionizing radiation; ultraviolet; pulsed light; ultrasound; high pressure; fresh-cut

Introduction

Fresh fruits and vegetables are rich in carbohydrates, fibers, vitamins, and other nutrients such as antioxidants and have been highly recommended by health professionals and organizations as part of a well-balanced daily diet to reduce the risk of heart disease, stroke, and development of certain types of cancer, diabetes, and many other health issues (Lavin and Lloyd 2012; Baselice et al. 2017; Singla, Chaturvedi, and Sandhu 2020). In order to meet the changes in lifestyle and requirements of convenience, fresh produce is minimally processed to 'fresh-cut' products. Fresh-cut produce, refers to 'any fresh fruit or vegetable or combination thereof that has been physically altered from its whole state after being harvested from the field (e.g., by chopping, dicing, peeling, ricing, shredding, slicing, spiralizing, or tearing) without additional processing (such as blanching or cooking)' (USFDA 2019). With rising income, increasingly busy lifestyles, and demands for convenience and health-benefits, the sale of fresh-cut produce has increased substantially over the last 2–3 decades in many countries (Del Gobbo et al. 2015; Baselice et al. 2017).

Unfortunately, the number of outbreaks of foodborne illnesses associated with fresh and fresh-cut produce has increased concomitantly in the U.S. and many other countries in recent years (Callejón et al. 2015; Del Gobbo et al. 2015; Bintsis 2017). The U.S. Centers for Disease Control and Prevention (CDC) estimated the number of foodborne illness from 31 major pathogens (Scallan et al. 2011). The 31 known pathogens acquired in the United States caused 9.4 million episodes of foodborne illness, 55,961 hospitalizations, and 1351 deaths every year. While norovirus has been shown to be responsible for the majority of produce-related illnesses in the U.S. and Europe, bacterial pathogens such as *Salmonella enterica*, Shiga toxin producing *Escherichia coli*, and *Listeria monocytogenes* often cause more serious harm and complications and number of deaths (Callejón et al. 2015; Carstens, Salazar, and Darkoh 2019). In addition, foodborne illnesses result in significant economic losses. According to the United States Department of Agriculture (USDA), the cost of foodborne illness is estimated to be $10–83 billion per year in the U.S. (USDA, 2014). The total number of reported outbreaks of foodborne illnesses associated with all foods decreased by 38% during 1998–2013 in the U.S. (Bennett et al. 2018). The percentage of outbreaks

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attributed to fresh produce among all outbreaks, however, increased from 8% during 1998–2001 to 16% during 2010–2013, suggesting that many other food industry sectors have improved their practices, while the fresh produce industry needs to adopt further preventive and control measures. The fresh produce industry is in urgent need of affective intervention technologies. Postharvest intervention is of vital importance to enhance the microbial safety of fresh produce. Over the years, many different types of postharvest intervention technologies and treatments have been developed including chemical, physical, and biological means. Some of the technologies show promise in inactivating human pathogens on fresh produce. However, there are few technologies that are commercialized. There are many reasons for the lack of adopting technology. One of reasons may be due to their undesirable effects on quality of fresh and fresh-cut produce, including surface discoloration), softening, and loss of nutrients such as vitamin C. While safety is a prerequisite of any food product, product quality and shelf-life often determine consumer acceptance and the success of any new processing technology. Quality of fresh produce is determined by a combination of parameters including appearance, texture, flavor, and nutritional value (Kader 2002; Barrett, Beaulieu, and Shewfelt 2010).

There are many recent reviews on various interventions, including conventional and emerging technologies in order to improve microbial safety of fresh and fresh-cut fruits and vegetables (Gil, Allende, and Selma 2011; Alexandre, Brandão, and Silva 2012; Pasha et al. 2014; Smetanska, Hunaefi, and Barbosa-Cánovas 2013; Warriner and Namvar 2013; Artes and Allende 2014; Mahajan et al. 2014; Nicola and Fontana 2014; Gil et al. 2015; Ali et al. 2018; Erkan and Yıldırım 2017; Ma et al. 2017; Mahajan et al. 2017; Singh, Walia, and Batra 2018; De Corato 2020). The present review focuses on the impact of physical interventions on quality of fresh and fresh-cut produce. We hope that this review can be useful for future research directions to minimize the unwanted quality changes, due to intervention technologies, and ultimately aiding to the implantation of effective technologies to enhance microbial safety of fresh produce. Non-thermal physical interventions to be discussed include ionizing radiation, UV, pulsed light, ultrasound, high hydrostatic pressure processing, and cold plasma.

Ionizing radiation

There are three common types of ionizing radiation: gamma ray, electron beam, and X-ray (Fan and Niemira 2020). Gamma rays are produced from a nuclear source (commonly cobalt-60 or cesium-137) and have excellent penetration capability. Electron beams produced often by accelerators, have low penetration abilities, but permits fast processing speeds (in seconds). X-rays have high penetration abilities and are converted from electron beams. All three types of ionizing radiation, at similar doses, have similar effects on human pathogens and product quality because all three exerts its effects through two mechanisms: direct effect and indirect effect (Fan 2012). For the direct effect, ionizing radiation directly causes damages to cell components such as DNA, carbohydrates, and lipids. For the indirect effect, free radicals and reactive species (such as hydrated electrons, hydrogen atoms, and hydroxyl radicals) from radiolysis of water react with cells or food components (Simic 1983). In fresh produce, water is the major component, therefore, the indirect effect is the major mechanism for the changes induced by ionizing irradiation.

At low doses (≤1 kGy), irradiation reduces populations of human pathogenic bacteria and spoilage microorganisms without significant losses in quality parameters such as color, firmness or sensory attributes of many fresh produce items, for example spinach and tomato (Fan, Niemira, and Sokorai 2003; Fan and Sokorai 2008) (Table 1). However, 2 kGy gamma irradiation decreased vitamin C content by 50% in fresh cilantro and 3 kGy had higher decay rate and off-odor scores due to irradiation-induced damages after 14 days of storage at 3 °C (Fan, Niemira, and Sokorai 2003a). Similarly, 2 kGy irradiation treatment reduced ascorbic acid content of spinach by 75% after 14 days storage at 4 °C while the appearance, aroma, texture, flavor, and overall ratings were not affected (Fan and Sokorai 2011). Another study showed that 1.0 kGy irradiation alleviated the loss in vitamin C content and inhibited polyphenol oxidase activity of fresh-cut lettuce during storage (Zhang et al. 2006). When applied as a disinfection technology, X-ray irradiation at doses up to 0.8 kGy did not affect soluble solids content, titratable acidity, or fructose concentrations of dragon fruit. However, glucose, sucrose, and total sugar concentrations decreased linearly with increasing doses (Wall and Khan 2008). Electron beam (1.0, 1.5 and 3.2 kGy) resulted in a loss in firmness of romaine lettuce (Han et al. 2004) and 3.2 kGy led to the loss of firmness and aroma of blueberry fruit (Moreno et al. 2007). It has been shown that low-dose electron beam treatments (1.0–1.5 kGy) increased carotene content in cantaloupes (Castell-Perez et al. 2004), while 1 kGy electron beam irradiation did not cause any effect on firmness, color, or flavor of fresh-cut watermelon (Smith et al. 2017).

There are some studies demonstrating that some fresh produce items can tolerate higher doses and even showing beneficial effects during post-irradiation storage. For example, irradiation (2 kGy) inhibited the change of titratable acidity and pH and reduced the population of microorganisms in Chinese cabbage during refrigerated storage (Ahn et al. 2005). Radiation (2.5 kGy) resulted in a lower spoilage rate and maintained ultrastructure of blueberries after 21–35 days of storage, compared to the nontreated control (Wang and Meng 2016). Irradiation (2 kGy) improved microbial safety without significant loss on total carotenes, ascorbic acid, and sucrose content of carrots (Kamat et al. 2005). It has also been shown that irradiation (2 kGy) reduced browning of cabbage without causing changes in phenolic acid content, even though a 1.4-fold decrease in phenylalanine ammonia lyase activity was observed (Banerjee et al. 2015) (Table 1). A 5 kGy radiation preserved antioxidant activity and total flavonoid content and increased content of total phenolics of watercress (Pinela

Table 1. Effects of ionizing radiation on quality attributes of fresh and fresh-cut produce.

Treatment conditions (concentration, time, intensity, dose etc.)	Type of fresh produce	Effect on quality	Reference
gamma irradiation (2 kGy)	cabbage	resulted in a 1.4-fold down-regulation in phenylalanine ammonia lyase enzyme activity and inhibited browning without change on phenolic acid content;	Banerjee et al. 2015
gamma irradiation (1, 2 and 5 kGy)	watercress	1 kGy dose decreased amount of polyunsaturated fatty acids; 2 kGy dose favored polyunsaturated fatty acids and 5 kGy dose better preserved the antioxidant activity and total flavonoids and favored monounsaturated fatty acids, tocopherols and total phenolics	Pinela et al. 2016
gamma irradiation 1 kGy	green onion	No significant loss in quality attributes (color, firmness, sensory, pigments)	Fan, Niemira, and Sokorai 2003b
gamma irradiation 2.5 kGy	blueberry	resulted in lower rot rate, higher firmness, relatively complete cell-wall ultrastructure and a long shelf life	Wang and Meng 2016
gamma irradiation 1.0 kGy	fresh-cut lettuce	alleviated loss in vitamin C content and inhibited polyphenol oxidase activity	Zhang et al. 2006
gamma irradiation 0, 1, 2, and 3 kGy	fresh cilantro	2 and 3 kGy decreased vitamin C content, 3 kGy had higher decay rate and off-odor scores	Fan, Niemira, and Sokorai 2003a
gamma irradiation 1, 2, 3, and 4 kGy	spinach	ascorbic acid content of irradiated sample decreased and appearance, aroma, texture, flavor and overall were not affected (up to 2kGy)	Fan and Sokorai, 2011
gamma irradiation 1 and 2 kGy and modified atmosphere packaging	Chinese cabbage	inhibited the change of titratable acidity and pH and reduced microorganisms significantly	Ahn et al. 2005
gamma irradiation 2 kGy	carrot	extended shelf life and improved microbial safety without significant loss on total carotenes, ascorbic acid, and sucrose content	Kamat et al. 2005
gamma irradiation 0.5 or 1 kGy and 47 °C water dipped for 2 min	fresh-cut iceberg lettuce	reduced undesirable effects on quality including firmness, vitamin C, and total antioxidants content	Fan, Toivonen, et al. 2003
gamma irradiation 1.5 kGy and 1% w/v carboxymethyl cellulose (CMC) coating	plum	chlorophyll retention and a lower rot rate and extended shelf life	Hussain et al. 2015
gamma irradiation 1.2 kGy and 1.0% (w/v) carboxymethyl cellulose coating	peach	prevented disease incidence up to 7 days during 30 days refrigeration storage.	Hussain et al. 2016
gamma irradiation 0, 1.0, 1.5 and 2.0 kGy	groundnut	prevent the fungal growth and aflatoxin content without adverse damage on quality including the protein content, oil content, peroxide value.	Osman et al. 2012
x-ray irradiation 0, 200, 400, 600, or 800 Gy	dragon	decreased glucose, sucrose, total sugar content, and firmness	Wall and Khan 2008
1.0, 1.5 and 3.2 kGy electron beam	romaine lettuce	a loss in firmness	Han et al. 2004
3.2 kGy electron beam	blueberry	firmness and aroma loss	Moreno et al. 2007
1.0-1.5 kGy electron beam	cantaloupe	increased carotene content	Castell-Perez et al. 2004
about1 kGy electron beam	watermelon	enhanced microbial safety without any effect on firmness and color, flavor	Smith et al. 2017
0.4 and 1 kGy electron-beam	mandarin oranges	efficient for reducing the aerobic plate counts, yeasts and molds, and coliforms in mandarins stored for up to 15 d irradiation did not affect its moisture, total phenolics, and vitamin C.	Nam et al. 2019
1, 2 or 5 kGy gamma and electron beam irradiation	*Agaricus bisporus* Portobello	irradiation type had higher effect than irradiation dose, while for the 5 kGy dose, independently of irradiation source, was linked with higher protein levels. And higher contents in sugars and ergosterol were found in gamma irradiation.	Cardoso et al. 2019
$\leq$ 1 kGy electron beam alone or in combination with MAP (Modified Atmosphere Packaging)	red grapes strawberries, and cherry tomatoes	$\leq$ 1 kGy alone, or in combination with MAP suppressed bioburden by at least 1 to 2 log units, no significant acceptability difference were found in consumer taste panel ($P \geq 0.05$) in terms of appearance, odor, color, firmness and flavor.	Smith et al. 2020

et al. 2016). However, the high dose likely resulted in the deterioration of sensory quality.

Since irradiation can result in quality deterioration, research has been conducted to combine ionizing radiation with other treatments to minimize the losses. For example, pre-irradiation warm water dipping combined with modified atmosphere packaging reduced undesirable effects of irradiation on quality of fresh-cut iceberg lettuce including firmness, vitamin C, and total antioxidants content (Fan, Toivonen, et al. 2003); calcium ascorbate treatment could alleviate the firmness loss and browning caused by ionizing radiation on fresh-cut 'Gala' apples (Fan et al. 2005). Combination of carboxymethyl cellulose coating and gamma irradiation resulted in chlorophyll retention and a lower rot rate for plums and peaches (Hussain et al. 2015, 2016).

Table 1 lists the studies related to ionizing radiation effects on quality of fresh and fresh-cut produce. Overall, ionizing radiation at low doses (1 kGy) did not significantly affect sensory quality or nutrient quality of fresh produce. At low doses, more than 5 log reductions of human pathogens on fresh produce could be achieved (Niemira 2008). Higher doses may result in the loss of nutrients, particularly vitamin C content. Irradiation may also increase phenolic contents and other phytochemicals in some produce items. The effect of irradiation depends on dose, type of fresh produce, and storage conditions. Another major effect of irradiation on fresh produce quality is immediate loss of firmness after irradiation. The loss of firmness may be related to irradiation-induced changes in cell wall components, such as hydrolysis of pectin, cell wall modifications, and pectin methyl esterase activity (Melo et al. 2018).

Even though low dose irradiation has been shown to be effective in reducing human pathogens on fresh produce without significant effects on produce quality, its application is very limited. The current uses of irradiating are mainly for phytosanitary purposes in order to meet quarantine requirements of disinfestation (Roberts and Follett 2017). One of the major factors limiting the commercial application of ionizing radiation is reluctance in consumer acceptance of the technology, mostly due to the misinformation and concern on using radioactive materials (Bearth *et al.* 2019). Educating consumers about the benefits and nature of ionizing radiation will aid in the acceptance and application of the technology. X-ray and electron beam technologies which do not involve the use of radioactive isotopes, may have advantages in terms of consumer acceptance. Overall, ionizing radiation is a relatively mature non-thermal technology and can be applied for niche products and markets to enhance microbial safety of foods, inhibit sprouting of tubers, and disinfesting against insects.

UV and pulsed light

Basing on wavelength, ultraviolet as a non-ionizing radiation can be divided into three groups: 100-280 nm (UV-C), 280–315 nm (UV-B), and 315–400 nm (UV-A). UV-C is the most effective germicidal UV light. The germicidal effect of UV-C light is a result of its ability to damage DNA or RNA of a microorganism and consequently blocking cell replication (Sinha and Häder 2002; Escalona et al. 2010). UV-C induces a variety of mutagenic and cytotoxic DNA lesions via photocatalytic formation of cyclobutane thymine dimers. Therefore UV-C light can effectively inactivate microorganisms, including pathogenic and spoilage microorganisms. UV-C technology does not leave chemical residue, nor requires extensive worker-protection equipment (Yousef and Marth 1988). Application of UV technology in continuous and pulse modes for processing whole and fresh-cut fruits have been discussed (Koutchma, Orlowska, and Zhu 2018). UV light treatment of fresh fruits and vegetable surfaces have been investigated to decontaminate surfaces, reduce decay, and enhance shelf life and quality (Turtoi 2013) (Table 2).

UV-C has been found to reduce microbial populations on fresh and fresh-cut produce without significant effects on quality. For example, lower dose UV-C light (4.1 kJ•m^{-2} at 254 nm) can achieve microbial reductions comparable to aqueous sanitizers, such as chlorine and ozone without affecting juice leakage, color, and overall visual quality of fresh-cut watermelon (Fonseca et al. 2006). On the surface of button mushroom, UV-C (0.45–3.15 kJ• m^{-2}) resulted in 0.67-1.13 log (CFU• g^{-1}) reductions of *E. coli* O157:H7 and 0.63–0.89 log (CFU• g^{-1}) total aerobic plate, without deterioration effects on quality (Guan, Fan, and Yan 2012). Furthermore, the UV-C treatment inhibited surface lesion and extended shelf-life, presumably due to its antimicrobial effect on *Pseudomonas* spp. that caused the lesion development. Water-assisted UV (samples were treated by UV while being immersed in agitated water) was found very effective in inactivating *Salmonella* on tomatoes and fresh-cut lettuce (Guo, Huang, and Chen 2017). In addition, combination of 2 kJ•m^{-2} UV-C and active modified atmosphere conditions, applied to cherry tomatoes stored at low temperatures, delayed *S.* Typhimurium growth, improved color and firmness, and lycopene content (Choi et al. 2015).

UV-C may be able to reduce browning of fresh and fresh-cut produce. UV-C treatment (75 W for 5 and 10 min) controlled browning of fresh-cut lotus root by inactivation of polyphenol oxidase, peroxidase, and phenylalanine ammonia lyase (enzymes involved in browning) and reduced soluble quinone content without causing changes in soluble solids content or firmness (Wang et al. 2019). Similarly, UV-C combined with warm water washing (45 °C, 120 s) deactivated the phenylalanine ammonia lyase, polyphenol oxidase, and peroxidase, as well as improved sensory qualities of fresh-cut endive (Hägele et al. 2016). Other ranges of UV may also have a positive role in inhibiting browning of apples and pears (Lante, Tinello, and Nicoletto 2016). However, UV-C is also found accelerating initial browning in cut-apples (Gómez et al. 2010) and mushrooms (Guan, Fan, and Yan 2012). Although samples treated with UV-C had more severe browning immediately after treatment, the control mushrooms browned faster during storage than the UV-C treated samples (Guan, Fan, and Yan 2012). The effect of UV may depend on dose, type of fresh produce, treatment time, and storage.

UV-C treatment could reduce decay in fruits and vegetables such as grapefruit (D'hallewin et al. 2000). Exposure of fresh-cut melon to UV-C light led to 2 log reductions of both total viable count and *Enterobacteriaceae*. Low microbial populations were maintained during storage with no significant effects on product color or firmness (Manzocco, Da Pieve, and Maifreni 2011). In addition, all three types of UV are able to induce resistance of fruits and vegetables to

Table 2. Effects of UV-C on quality attributes and microbial populations of fresh and fresh-cut produce.

Treatment conditions (concentration, time, intensity, dose etc.)	Type of fresh produce	Effect on quality	Reference
UV-C 4.1 kJ•m^{-2} at 254 nm	fresh-cut watermelon	reduced microbial populations without affecting juice leakage, color, and overall visual quality	Fonseca et al. 2006
UV-C 0, 0.3, 1.5, 3, 6, 12 kJ•m^{-2} corresponding to 0, 1, 5, 10, 20, and 40 min at 4 °C respectively	fresh-cut lotus root	controlled browning by inactivation of polyphenol oxidase, peroxidase, and phenylalanine ammonia lyase and reduce soluble quinone content without change on soluble solids content and firmness (5 and 10 min)	Wang et al. 2019
UV-C 1.2 kJ•m^{-2} and warm (45 °C, 120 s) water washing	fresh-cut endive	disactivated the phenylalanine ammonia-lyase, polyphenol oxidase, and peroxidase and improved sensory qualities significantly	Hägele et al. 2016
Water-assisted UV 29 mW•cm^{-2} for 2min (samples were treated by UV while being immersed in agitated water)	grape tomato and fresh-cut lettuce	Reduced populations of *Salmonella* by 3.84 and 1.79 log CFU•g^{-1} from 6.14 and 8.23 log CFU•g^{-1}, on tomato and lettuce, respectively.	Guo et al. 2017
UV-C 0.5, 1.5, or 3.0 kJ·m^{-2}	grape	0.5 kJ·m^{-2} reduce decay, irradiation at dosages >0.5 kJ·m^{-2} did not further improve decay control and caused rind browning and necrotic peel	D'hallewin et al. 2000
UV-C 7 kJ•m^{-2}	pepper	reduced decay and chilling injury	Vicente et al. 2005
UV-C 10, 15 or 25 min (5.6 ± 0.3; 8.4 ± 0.5 and 14.1 ± 0.9 kJ•m^{-2}, respectively)	cut-apple	accelerated browning	Gómez et al. 2010
UV-C 2 kJ•m^{-2}	peeled garlic	increased antioxidant content including total polyphenol, flavonoid, apigenin and quercetin levels, improved firmness during storage for peeled garlic after storage	Park and Kim 2015
UV-C 0.45–3.15 kJ•m^{-2}	button mushroom	0.67–1.13 and 0.63-0.89 log CFU•g^{-1} reduction of *E. coli* O157:H7 and total aerobic plate, respectively, inhibited surface lesion and extended shelf-life without deterioration effects on quality	Guan et al. 2012
UV-C 0, 3.7 × 10^{3} J•m^{-2}, 24.4 × 10^{3} J•m^{-2}	tomato	a reduction in respiration rate, ethylene production, and an increase in putrescine	Maharaj et al. 1999
UV-C 1.6, 2.8, 4.8 and 7.2 kJ•m^{-2}	watermelon	increased total antioxidant capacity with slight effect on color, lycopene	Artés-Hernández et al. 2010
UV-C 0, 1200, 6000 and 12,000 J•m^{-2}	fresh-cut melon	inhibited microbial growth, decreased leakage, and induced better flavor	Manzocco et al. 2011
UV-C 2 kJ•m^{-2} and passive and active modified atmosphere	cherry tomato	improved the color and firmness, and lycopene content and delayed *S.* typhimurium growth	Choi et al. 2015
UV-C 0, 3.4, 7.2 and 10.5 kJ•m^{-2}	Tahitian limes	the highest UV-C treatment (10.5 kJ•m^{-2}) maintained low ethylene production and low respiration rates and had a 60% acceptability index after 28 days storage with no differences between the different UV-C intensities and no effect on fruit weight loss, TSS or TA contents	Pristijono et al. 2019
UV-B 2.30, 3.60, and 4.80 W•m^{-2} for 4, 6, 8, and 10 h respectively	sweet basil	3.60 W/m^{2} was the best which increased total flavonoid, total phenol, quercetin, catechin, kaempferol, rutin, ferulic acid, gallic acid and chalcone synthase (CHS) activity, induced cinnamic acid and luteolin	Ghasemzadeh et al. 2016
UV-A 2.43 × 10^{-3} W•m^{-2} for up to 60 min	apple and pear	antibrowning effects on cut surfaces	Lante et al. 2016
UV-C 1, 2, 4, 8 J•cm^{-2} (0.95, 1.9, 3.8 and 7.6 s each side, respectively)	tomato	enhanced antioxidant capacity by increasing lycopene, total carotenoid, phenolic compounds content without effect on pH and soluble solid content	Pataro et al. 2015
UV-C 1.5, 3 J•cm^{-2}	spinach	In stage II (baby spinach), a decrease in vitamin C content but an increase with total plate count along with the number of applications was observed after applying 3 J•cm^{-2}. Maintained the meshophilic and yeast counts during the spinach development in the field and reduced the mesophilic count after storage.	Martínez-Sánchez et al. 2019
UV-C 9 J•cm^{-2}	Apple	Treatment decreased the malate content and no changes in sugar content was found, higher ratio of total sugars to total organic acids.	Onik et al. 2020

postharvest spoilage by activating genes encoding pathogenesis-related proteins, leading to the accumulations of phytoalexins.

It is well known that UV-C increased antioxidants of fresh and fresh-cut produce by promoting synthesis of secondary metabolic compounds. For example, UV-C ($2\,kJ{\bullet}m^{-2}$) increased antioxidants content including total polyphenol, flavonoid, apigenin, and quercetin levels of peeled garlic during storage (Park and Kim 2015). In another study, UV-C increased total antioxidant capacity with slight effects on lycopene of fresh-cut watermelon (Artés-Hernández et al. 2010). In addition, research has shown that UV-B ($3.60\,W{\bullet}m^{-2}$ for up to 10 h) increased the amount of total flavonoid, total phenol, and several individual phenolic compounds of sweet basil, which resulted in higher antioxidant capacity and pharmaceutical properties (Ghasemzadeh et al. 2016). Furthermore, UV-C enhanced antioxidant capacity of tomato and apple during storage by increasing lycopene, total carotenoid, and phenolic compounds content (Pataro et al. 2015) without effects on pH or titratable acidity. UV-C as an abiotic stress induces synthesis of secondary metabolites with antioxidant activities by increasing activities of enzymes in the phenylpropanoid pathway (Cisneros-Zevallos, 2003).

UV-C can also delay the ripening process of fruit. After treated by UV-C, the tomato fruit showed a reduction in respiration rate, ethylene production, and an increase in putrescine (Maharaj, Arul, and Nadeau 1999). In addition, it reduced chilling injury of pepper (Vicente et al. 2005). However, the impact of UV is related to its dose, treatment time, storage temperature, produce type, and packaging. The various effects of UV-C on quality attributes of fresh and fresh-cut produce are listed in Table 2.

Pulsed light as an emerging physical non-thermal technology, is capable of inactivating various microorganisms within a very short time, on food contact surfaces, equipment, and food packaging materials (Gómez et al. 2012, Ramos-Villarroel et al. 2012a; Charles et al. 2013). Pulsed light involves the use of short-duration, high-peak pulses of broad-spectrum light (100–1100 nm; UV to near infrared) (Oms-Oliu, Martín-Belloso, and Soliva-Fortuny 2010). As a physical preservation method, pulsed light has a positive consumer image. This technology was approved by the U.S. FDA for food processing. It is generally believed that the UV-C component of pulsed light is the most important wavelength region for its bactericidal effects due to the indispensable effect of the UV portion (Ramos-Villarroel et al. 2012a). However, pulsed light is different from UV-C light, because pulsed light destructs microorganisms via multiple mechanisms including inter-related photochemical, photothermal, and photophysical effects (Farrell et al. 2011; Kramer and Muranyi 2014; Rowan, Valdramidis, and Gómez-López 2015). As a multi-target technology, pulsed light is more effective in inactivating microorganisms in a relatively short period of time than continuous UV-light (Scott et al. 2017).

Pulsed light as a relatively novel technology has been evaluated for a number of fresh and fresh-cut produce and exhibits similar beneficial effects as UV-C on fresh produce such as extension of shelf-life, reductions of microbial populations, inhibition of ripening process, and induction of antioxidant compounds (Abida, Rayees, and Masoodi 2014) (Table 3).

Pulsed light extended the shelf-life of fresh-cut mushrooms with slight effects on texture and antioxidant capacity (Oms-Oliu, Aguiló-Aguayo, et al. 2010). Repetitive pulsed light treatments were effective in extending shelf-life of fresh-cut cantaloupe by maintaining its physical quality (firmness, fluid loss, and color), chemical quality (pH, titratable acidity, total soluble solids, phenolic content and ascorbic acid content), and had minimal effect on tissue structure (Koh et al. 2016). The shelf life of fresh-cut cantaloupes was extended by 20 days at 4 °C compared to control in terms of microbiological quality. The extension of shelf-life is due to the reduction of spoilage microorganisms and maintenance of quality attributes. For example, pulsed light reduced populations of native mesophilic bacteria and inoculated *Bacillus cereus* by 1.0–1.3 log and 1.3–2.0 log, respectively, without causing significant changes on vitamin C, total phenolics, antioxidant capacity, firmness and color of plums, tomatoes, cauliflowers, sweet peppers, and strawberries (Luksiene et al. 2012). Exposure of fresh-cut avocado to pulsed light ($14\,J{\bullet}m^{-2}$) resulted in reductions of mesophilic microorganisms (1.20 log ($CFU{\bullet}g^{-1}$), delay of the proliferation in yeasts and molds count of fresh cut avocado, and prolonged microbiological shelf life up to 15 days at 4 °C (Aguiló-Aguayo et al. 2014). Similarly, intense light pulse (15 or 30 pulses and $0.4\,J{\bullet}cm^{-2}$ per pulse) decreased ethylene production while inactivating *L. innocua* and *E. coli* of avocado cylinders (Ramos-Villarroel, Martín-Belloso, and Soliva-Fortuny 2011).

Like UV treatment, pulsed light can induce synthesis of many health-beneficial phytochemicals. For example, pulsed light was useful for fig fruits to enhance red coloration and increase anthocyanin synthesis (Rodov, Vinokur, and Horev 2012). It seemed that pulsed light activated antioxidant defense mechanisms as evidenced by increased activities of superoxide dismutase (SOD) and catalase, and contents of carotenoid, vitamin C, flavonoid, anthocyanin and total phenolics in 'Tommy Atkins' mangoes (Lopes et al. 2016). For immature green tomatoes, pulsed light increased lycopene, total carotenoid, phenolic compounds, and antioxidant capacity (Pataro et al. 2015). A $5.0\,J{\bullet}cm^{-2}$ (30 s) pulsed light treatment reduced *Salmonella* and *E. coli* O157:H7 populations and improved nutritional quality of raspberries (Xu and Wu 2016).

As with any technology, high doses of pulsed light can result in detrimental effects on sensory and nutritional quality of fresh produce. For example, high doses (12 and $28\,J{\bullet}cm^{-2}$) had adverse effects on phenolic compounds, vitamin C, and antioxidant capacity of fresh cut mushroom, probably due to thermal damage induced by the treatments (Oms-Oliu, Aguiló-Aguayo, et al. 2010). Pulsed light at doses above $17.5\,kJ{\bullet}m^{-2}$ caused dehydration, browning, and

Table 3. Effects of pulsed light on quality attributes and microbial populations of fresh and fresh-cut produce.

Treatment conditions (concentration, time, intensity, dose etc.)	Type of fresh produce	Effect on quality	Reference
4.8 J•cm^{-2} 12 and 28 J•cm^{-2} 15days at 4 °C	fresh-cut mushroom	4.8 J•cm^{-2} extended the shelf-life with slight effect on texture and antioxidant capacity; 12 and 28 J•cm^{-2} had adverse effects on phenolic compounds, vitamin C and antioxidant capacity	Oms-Oliu, Aguiló-Aguayo, et al. 2010
17.5, 52.5, 105.0 and 157.5 kJ•m^{-2}	apple	Doses beyond 17.5 kJ•m^{-2} caused dehydration, browning and flavor depletion	Ignat et al. 2014
15 or 30 pulses and 0.4 J•cm^{-2} per pulse	avocado	decreased ethylene production and disactivated the *L. innocua* and *E. coli* effectively, but the use of 30 pulse caused browning and softening	Ramos-Villarroel et al. 2011
2.7, 7.8, 11.7 and 15.6 J•cm^{-2}	cantaloupe	extended shelf-life with no effect on its physical quality (firmness, fluid loss, color) and chemical quality (pH, titratable acidity, total soluble solids, phenolic content and ascorbic acid content) and minimal effect on tissue structure (7.8 J•cm^{-2} is the best)	Koh et al. 2016
10, 30, 90 and 300 s, with fluence values of 2, 6, 18 and 60 kJ•m^{-2}, respectively	fig	enhanced red coloration and increased anthocyanin content	Rodov et al. 2012
8 J•cm^{-2}	'Kent' mango	maintained firmness, color, carotenoid content, phenol and total ascorbic acid content	Charles et al. 2013
0.6 J•cm^{-2}	'Tommy Atkins' mango	activated antioxidant defense mechanisms in pulp (high activity of SOD and CAT, more carotenoid, vitamin C, flavonoid, anthocyanin and total phenolics) and peel (SOD and carotenoid, mangiferin, and total phenolics)	Lopes et al. 2016
1, 2, 4, and 8 J•cm^{-2} each side (0.95, 1.9, 3.8 and 7.6 s each side, respectively) and 2, 4 J•cm^{-2} each side (1 h, 2 h respectively)	green tomato	increased lycopene, total carotenoid, phenolic compounds, and antioxidant capacity	Pataro et al. 2015
3.7 kJ•m^{-2} UV vs 4.6 kJ•m^{-2}/pulse (8, 16, 24 pulse)	mature green tomato	high intensity pulsed polychromatic light delayed ripening and enhanced disease resistance	Scott et al. 2017
5.0 J•cm^{-2} 30 s	raspberry	reduced *Salmonella* and *E. coli* O157:H7 and improved nutritional quality	Xu and Wu 2016
2, 10, 20 and 40 s, corresponding to fluences of 2.4, 11.9, 23.9 and 47.8 J•cm^{-2}, respectively	strawberry	reduced softness and fungal incidence	Duarte-Molina et al. 2016
Pulsed UV light dose 5.4 J•cm^{-2}, 5 Hz	plums, tomato, cauliflower, sweet pepper and strawberry	reduced naturally distributed mesophilic bacteria and inoculated *Bacillus cereus* by 1.0-1.3 log and 1.3-2.0 log, respectively, and no significant change on vitamin C, total phenolics, antioxidant capacity, firmness, and color	Luksiene et al. 2012
3.6, 6.0 and 14 J•cm^{-2} per side	fresh-cut avocado	highest reductions in aerobic mesophilic microorganisms (1.20 log CFU•g^{-1}) and better hue values and 1.3-fold of chlorophyll a and b were observed after 6.0 J•cm^{-2} treatments.	Aguiló-Aguayo et al. 2014
Intense pulsed light 0, 2, 5, 10, 15, 20 and 30 pulses corresponding to 0, 8, 20, 40, 60, 80 and 120 kJ•m^{-2}, respectively	spinach	a higher respiration rate and antioxidant content just after treatment followed by accelerated deterioration in physicochemical quality	Agüero et al. 2016
1.0 to 3.0 kV (0.1 and 1.0 J•cm^{-2} fluency at a distance of 10 cm)	endive salad and mung bean sprout	a discoloration and high respiration rate of endive salad while an improvement on color without affecting the respiration of mung bean sprouts	Kramer et al. 2015
Full spectrum-light pulses (6 and 12 J•cm^{-2})	fresh-cut watermelon	negative effects on the color and texture	Ramos-Villarroel et al. 2012b

(*continued*)

Table 3. Continued.

Treatment conditions (concentration, time, intensity, dose etc.)	Type of fresh produce	Effect on quality	Reference
7.86 J●cm2 and 9.38 J●cm^{-2}	potato	enhanced extraction of steroidal alkaloids from potato peel	Hossain et al. 2015
water-assisted pulsed light (immersed in agitated water during treatment 1.27 J●cm^{-2}) for 5-60s	blueberry	maintained color and reduced sample heating significantly	Huang and Chen 2014
gellan-gum based coating (0.5% w/v) with apple fiber followed by pulsed light (12 J●cm^{-2})	fresh-cut apple	reduced softness and browning without affecting its flavor	Moreira et al. 2015
1% w/v N-acetylcysteine and 0.5% w/v $CaCl_2$), combine pulsed light (8 and 16 J●cm^{-2})	fresh-cut 'Golden delicious' apple	increased phenolic and vitamin C content	Llano et al. 2016)
Pulsed light- 1.27 J●cm^{-2} and 10ppm SDS	green onion	enhanced microbial safety with no effect on quality	Xu, Chen, and Wu 2015
high intensity light (2500 lx), low intensity light (500 lx)	fresh-cut romaine lettuce	inhibited browning by decreasing browning-related enzymes (polyphenol oxidase and peroxidase) and preserving total phenol and ascorbic acid along with weight loss	Zhan et al. 2012
Pulsed light (1–63J●cm^{-2}) and HEN sanitizer (hydrogen peroxide, EDTA and nisin) wash (2 min)	spinach	The optimal treatment dose of 15.75 J●cm^{-2} resulted 2.7 log(CFU●g^{-1} reduction of *E. coli* O157:H7 while a rapid 2 min wash of HEN, provided 1.8 log CFU●g^{-1}. And the PL-HEN treatment significantly reduced spoilage microbial populations (> 5 log reduction) without visual and firmness quality	Mukhopadhyay et al. 2019
3 J●cm^{-2} (0.1 J●cm^{-2} per pulse) 5 J●cm^{-2} (0.1 J●cm^{-2} per pulse) 3 J●cm^{-2} of PL exposure (0.05 J●cm^{-2} per pulse)	strawberry	no significant or negligible difference in the 3 pulse light treatments PL comparing to the control group in weight loss, firmness, total anthocyanin, total phenolics, and total antioxidant activity. extending the shelf life.	Cao et al. 2019
Pulsed light (1–63 J●cm^{-2}) and LAPEN sanitizer (2 min)	cherry tomato stem scars	The optimal dose 31.5 J●cm^{-2} provided 2.3 log reduction of *Salmonella* while a 2 min wash in LAPEN sanitizer provided 2.1 log reduction on stem scars. Treatment of PL-LAPEN demonstrated more than 5 log reduction without significant influence on firmness and visual appearance quality but on texture.	Leng et al. 2019
repetitive pulsed light (RPL, 0.9 J●cm^{-2} at every 48 h up to 26 days), and or alginate (1.86%, w/v)	fresh-cut cantaloupes	Combination of alginate with RPL reduced accumulation of lactic acid and more effective than individual treatment in retaining total aroma compound.	Koh et al. 2019

flavor depletion of fresh cut apple (Ignat et al. 2014). Similarly, pulsed light (30 pulse, 0.4 J●cm^{-2} per pulse) caused browning and softening of avocado cylinders (Ramos-Villarroel, Martín-Belloso, and Soliva-Fortuny 2011). Furthermore, color and texture of raspberries treated with 30 s pulsed light (28.2 J●cm^{-2}) changed negatively during 10 days of storage, while the initial reductions of *Salmonella* and *E. coli* could not be maintained (Xu and Wu 2016). Some research showed that intense light pulse might not be applicable on fresh-cut vegetables, such as cabbage and lettuce due to detrimental changes in sensory quality (Gómez-López et al. 2005). In addition, it led to a higher respiration rate after treatment, followed by accelerated deterioration in physicochemical quality of spinach during storage (Agüero et al. 2016), resulted in a discoloration and high respiration rate of endive salad (Kramer, Wunderlich, and Muranyi 2015), and had negative effects on the color and texture for fresh-cut watermelon (Ramos-Villarroel et al. 2012b).

Pulsed light has been combined with coating and surfactants to enhance its effects. For fresh-cut apples, gellan-gum based coating (0.5% w/v) with apple fiber followed by pulsed light (12 J●cm^{-2}) reduced softness and browning without affecting their flavor (Moreira et al. 2015). Furthermore, when combined with coating with alginate, shelf life of fresh-cut cantaloupes was further extended by 28 days compared with samples with the pulsed light alone (Koh et al. 2017). Similar results could be found when pulsed light was combined with pectin-based edible coating, although off-odors in fresh-cut apple were detected (Moreira et al. 2017). When berries in water were treated with pulsed light, the efficacy of pulsed light against human pathogen was significantly higher than direct pulsed light (without water). The water-assisted pulsed light treatment had minimal or no effect on shelf-life, quality attributes, or nutritional compounds (Cao, Huang, and Chen 2017). When combined with quality-stabilizing dip (1% w/v N-acetylcysteine and 0.5% w/v $CaCl_2$), pulsed light (8 and 16 J•cm^{-2}) helped maintain a better quality and antioxidant characteristics of fresh-cut apples for 15 days at 5 °C (Llano et al. 2016). When combined with surfactants such as sodium dodecyl sulfate, pulsed light enhanced microbial safety of green onions with no effect on quality (Xu, Chen, and Wu 2015).

Both UV-C and pulsed light are shown to reduce populations of pathogenic and spoilage microorganisms on fresh and fresh-cut produce. In addition, they are capable of increasing the formation of many health beneficial compounds and antioxidant activity. The treatments may induce or inhibit browning of cut surface of fresh produce depending on dose, treatment temperatures, and storage. The treatments, especially pulsed light may result in other undesirable changes on some fresh-cut produce items such as fresh-cut leafy greens. In general, pulsed light is more effective than UV-C because of its high intensity and multiple target mechanisms. Perhaps, the major challenge for the application of UV-C and pulsed light on fresh and fresh-cut produce to enhance microbial safety, is their low penetration ability. The shading effect due to overlap or shading of fresh and fresh-cut produce items prevents uniform and complete light exposure of all produce surfaces. Double sided light treatments or introduction of a rotating/tumbling device may help to achieve the goal of uniform and complete exposure of UV or pulsed light (Fan, Huang, and Chen 2017). To assess UV/pulsed light dose received by a piece of fresh produce, film dosimetry systems may be applied (Yan et al. 2017).

Ultrasound

The inactivation of microorganisms by ultrasound is a consequence of cavitation (Majid, Nayik, and Nanda 2015; Serna-Galvis et al. 2016). As ultrasound waves propagate in water or other liquids, small bubbles form. The bubbles grow until reaching a critical size and then collapse violently, causing thermal, mechanical, and chemical effects. de São José et al. (2014, 2015) summarized ultrasound application in fresh fruit and vegetable products including effects on microbiota contamination, enzymes, and food components.

Ultrasound has been investigated in combination with other sanitizers, such as chlorine to enhance their antimicrobial efficacy. Its efficacy is, however, limited, often achieving 1–2 log or less reductions of pathogens on fresh produce after a few minutes of treatment under laboratory settings (de São José et al. 2014). For example, Zhou, Feng, and Luo (2009) observed that use of ultrasound (200 W•L^{-1}) contributed to a reduction of 0.7–1.1 log (CFU•g^{-1}) of *E. coli* O157:H7 in spinach compared with treatments using only chemical sanitizers. Ultrasound in combination with electrolyzed water resulted in 1.77 and 1.29 log reductions on total aerobic bacteria and 1.50 and 1.29 log reductions on yeasts and molds, respectively, for cherry tomatoes and strawberries (Ding et al. 2015).

Ultrasound treatment (106.19 W•L^{-1}, 25 °C) of cherry tomato fruit in water reduced spoilage microorganisms, delayed the ripening process by inhibiting ethylene production and respiration rate, and maintained color, flavor, firmness, and antioxidant capacity of the fruit (Wang et al. 2015). A recent study suggested that bananas that were treated by ultrasound (40 kHz) in water at 25 °C for 10 min developed less severity of chilling injury during storage at 5 °C (Khademi, Ashtari, and Razavi 2019). The combination of ultrasound (25 kHZ, 2 kW, 1 min) with chlorine or peroxyacetic acid did not cause tissue damage measured with electrolyte leakage, total color difference, or firmness during a 14-day storage at 4 °C (Salgado et al. 2014). Similar results were reported that the combination of ultrasound (130 W, 42 kHz, 0–30 min) and chlorine did not affect visual quality of fresh-cut lettuce during an 8-day storage at 5 °C (Irazoqui et al. 2019). However, confocal imaging indicated that ultrasound damaged the lettuce tissues, resulting in higher microbial growth that occurred during storage in treated samples.

Ultrasound can cause damages to fresh and fresh-cut produce. For example, ultrasound (40 kHz, 200 W for 5 and 10 min) resulted in lower pH and hue angle of fresh-cut potatoes during post-treatment storage (12 °C) (Amaral et al. 2015). Combination of ultrasonic treatment and electrolyzed water reduced firmness of cherry tomatoes, while other quality attributes such as soluble solids and acidity were not affected (Ding et al. 2015). Mustapha et al. (2020) recently reported that ultrasound (10 min, 20/40 kHz) alone or in combination with peracetic acid (40 mg•L^{-1}) or H_2O_2 (5%) resulted in loss of tomato firmness, even though up to 3.1 log reductions of natural microbiota were observed. Another study showed that lettuce leaves treated with ultrasound (26 kHz, 200 W 5 min) had lower scores of sensory quality attributes after 10 days of storage at 5 °C (Neto et al. 2019). After Romaine lettuce leaves were treated with ultrasound (25 kHz) at 26 W/L for 1–3 min, quality was not immediately affected (Yu, Engeseth, and Feng 2016). During 60 h storage at ambient temperature, an increase in phenylalanine ammonia lyase activity was observed, resulting in formation of phenolic compounds and enhancement of antioxidant capacity. The changes in quality of fresh produce due to ultrasound are related to the burst of cavitation bubbles, which results in localized high temperature and pressure. The transient high pressure and temperature cause the rupture of the cell membrane leading to the cellular leakage, loss of turgor pressure and tissue softening. The loss of tissue integrity also results in changes in enzymatic reactions and consequently the formation of secondary metabolites.

In summary, ultrasound-assisted washing of fresh produce has shown to enhance sanitation efficacy of aqueous sanitizers mainly due to the physical effects of acoustic cavitation (Palma, Zhou, and Feng 2017). However, its efficacy is often limited achieving ~1 log reduction compared with sanitizers themselves. In addition, cavitation and burst of bubbles during ultrasound treatment would also disrupt cell

Table 4. Effects of high pressure on quality attributes and microbial populations of fresh and fresh-cut produce.

Treatment conditions (concentration, time, intensity, dose etc.)	Type of fresh produce	Effect on quality	Reference
400 MPa for 2 min at 4 °C	iceberg lettuce and strawberry	inactivated murine norovirus with a slight influence on food quality	Lou et al. 2011
High pressure carbon dioxide treatment (12 MPa, 40 °C, 15 min)	fresh-cut carrot	maintained bioactive compound (phenol, flavonoid, carotenoid, antioxidant capacity) and enzyme stability and inactivated the natural microbial flora though texture and ascorbic acid loss	Spilimbergo et al. 2013
High pressure argon treatment (150 MPa for 10 min)	fresh-cut apple	delayed browning and microbial growth, reduced total phenolics loss without effect on titratable acidity and soluble solids for at cold storage	Wu, Zhang, and Wang 2012
High pressure argon treatment (1.8 MPa, 60 min 4 °C)	fresh-cut pineapple	extended shelf-life	Wu, Zhang, and Adhikari 2012
High pressure nitrogen treatment (120 MPa 10min)	fresh-cut pear	inhibited microbial growth, maintained sensory quality, and improved total phenolics without affecting titratable acidity and soluble solids	Xu, Liu, et al. 2015
high-pressure carbon dioxide and high-power ultrasound (12 MPa, 10 W, 40 °C, 20 min)	fresh-cut coconut	8 log reductions of S. Typhimurium with almost no effect on physicochemical quality including total acidity, pH, texture, color, enzymatic activity, antioxidant capacity, flavonoids, phenolic acids, phenols and dry matter, fat content	Ferrentino et al. 2015
peroxyacetic acid (100 mg•L^{-1}) dip for 2min in combination with: (a) vacuum (V: 10 mbar) or (b) positive pressure application (P: 3 bar).	lettuce	reduced microorganism population, it also had detrimental effect on the visual quality	Petri et al. 2015
400 MPa and 5 min for HHP, 1.2×10^5 J•m^{-2} for pulsed light, modified chitosan containing a nanoemulsion of mandarin essential oil	green beans	had antagonistic effect against *L. innocua* though with impact on green beans color and firmness	Donsì et al. 2015

wall and membrane structures of fresh produce causing cellular leakage, resulting in the loss of turgor pressure and consequent changes in texture, especially to fresh-cut leafy greens. Because of electric leakage, compromised tissue integrity, and consequent availability of nutrients to microorganism, the initial reduction of microorganisms may not be maintained during post-treatment storage. Taken together, the commercial application of ultrasound to enhance microbial safety of fresh and fresh-cut produce remains a challenge.

High pressure processing

High hydrostatic pressure (HHP) processing, also called high pressure processing, uses hydrostatic pressures commonly in the range of 100–800 MPa to treat various food products (Martínez-Monteagudo and Balasubramaniam 2016). Application of the high pressure for a period of 30 s to a few minutes inactivates microorganisms including pathogenic bacteria, native microflora, yeast and mold in foods, therefore enhancing microbial safety and extending shelf life (Hwang and Fan 2015; Wang et al. 2016). The inactivation of microorganisms is due to pressure induced damage on cell membrane and cellular integrity, which result in altered cell permeability, loss of osmotic regulation and genetic functions, and altered biochemical reactions (Barba et al. 2015) (Table 4).

While high pressure induces cellular injury to microorganisms, it certainly can cause similar damage to plant cells as well. For example, high pressure (300 MPa) led to a significant detrimental effect on the visual quality of lettuce (Petri, Rodríguez, and García 2015). High pressure (400–600 MPa for 2 min at 4 °C) resulted in considerable textural loss of blueberries, strawberries, and raspberries due to pressure-induced softening of the tissue even though the treatment inactivated murine norovirus, a surrogate for human norovirus, in low temperature and neutral pH (Lou et al. 2011). HHP (400 MPa 5 min) with or without combinations of chitosan coating or pulsed light had a significant impact on firmness and color of green beans even though HHP had antagonistic effects on *Listeria innocua* (Donsì et al. 2015). HHP treatment disturbs the cell permeability of fruits and vegetables. This altered cell permeability enables movement of water and metabolites in the cell. The degree of cell disruption is not only dependent on the extent of applied pressure level but also on the type of plant cell (Oey et al. 2008).

Because high pressure caused significant changes in the quality of fresh produce, especially in texture, relative lower pressure has been investigated often in combination with pressurized gases. High pressure carbon dioxide treatment (12 MPa, 40 °C, 15 min) (pressured CO_2) of fresh-cut carrots maintained bioactive compounds (phenol, flavonoid, carotenoid, antioxidant capacity) and microbial stability for 4 weeks at 4 °C. However, texture and ascorbic acid losses were 90% and 40% respectively (Spilimbergo et al. 2013). The high pressure treatment at a lower temperature (22 °C) did not exhibit microbial stability after 2 weeks of storage, due to a faster growth rate during storage compared with untreated samples.

High pressure nitrogen treatment (120 MPa 10 min) of fresh-cut pears inhibited microbial growth, maintained sensory quality, and improved total phenolics without affecting titratable acidity and soluble solids during storage (Xu, Liu, et al. 2015). High pressure argon treatment (150 MPa for 10 min, 4 °C) delayed browning and microbial growth, and reduced total phenolics loss without effects on titratable acidity and soluble solids for fresh-cut apples during storage at 4 °C (Wu, Zhang, and Wang 2012). Application of high pressure argon treatments maintained quality of fresh-cut pineapples during cold storage and extended the shelf life by 6 days at 4 °C (Wu, Zhang, and Adhikari 2012). The delay in the growth of microbes was probably due to argon or nitrogen dissolved in pineapple tissues and reduced water activity.

Combination of high-pressure carbon dioxide and high-power ultrasound technique (12 MPa, 40 °C, 20 min) achieved 8 log reductions of *S.* Typhimurium with almost no effect on physicochemical quality including total acidity, pH, texture, color, enzymatic activity, antioxidant capacity, flavonoids, phenolic acids, phenols and dry matter, or fat content of fresh-cut coconut (Ferrentino, Komes, and Spilimbergo 2015).

In general, to achieve significant reductions (>1 log) of pathogenic bacteria at ambient or low temperatures, the pressure of 300-600 MPa was required. For example, HHP (300 MPa, 8 °C for 5 min) inactivated populations of *Salmonella* and *Listeria* spp. in cantaloupe puree by 2.4 ± 0.2 and 1.6 ± 0.5 log (CFU•g^{-1}), respectively (Mukhopadhyay et al. 2016). The pressure at the range (300-600 MPa) likely results in adverse changes in the quality of fresh and fresh-cut produce. As mentioned earlier, pressure affects cell wall and membrane, which are associated to cell turgor of fresh and fresh-cut produce. At low pressure levels, the effect of cell turgor is reversible, reflected by the reestablished membrane semi-permeability and functionality of membrane-bound proteins. However, above a certain threshold, the effect of pressure become irreversible, resulting in tissue damage (Rux et al. 2019, 2020). The threshold was 100 MPa for most fresh and fresh-cut produce. One of the major effects of HHP is loss of firmness due to the failure of maintaining cell turgor and the overall tissue structure of the produce.

Fresh and fresh-cut produce are ‘living’ organisms and tissues. A living organism or tissue undergoes physiological processes such as respiration and other controlled metabolism activities. Furthermore, it can respond to abiotic and biotic stresses by synthesizing defense related compounds, such as secondary metabolic compounds (Toivonen and DeEll 2002). After treatments with high pressure at pressure above the thresholds, the fresh or fresh-cut produce can probably not be regarded as ‘living’ organisms because the cell integrity is lost and tissues fail to orchestrate a response to stresses, even though certain activities such as enzymes may be active.

Another characteristic of a living plant or tissue is compartmentation of metabolism and other cellular functions (Lunn 2007). The loss of cellular compartmentation due to HHP will allow release of enzymes and other compounds which come in contact with one another, resulting in dysfunction of metabolism. Therefore, it is questionable that HHP can be used to treat fresh and fresh-cut produce to enhance microbial safety of fresh produce, although combination of HHP with other techniques, such as pressurized gases may allow the use of low pressure to minimize the damage to fresh produce. It is also debatable whether the products treated by HHP can be claimed as fresh or fresh-cut produce, while they can certainly be regarded as minimally processed as HHP maintains a better sensory and nutritional quality than traditional thermal treatment (such as canning processing). Due to the cost associated with HHP, its use may be only for niche market and high value products.

Cold plasma

Plasma refers to ionized gas consisting of particles including photons, free electrons, excited or non-excited atoms, and positive or negative ions and molecules (Fernández et al. 2012). In addition, UV light and oxidants such as ozone and hydrogen peroxide are produced during the processing. Cold plasma is also referred as nonthermal plasma or atmospheric cold plasma because it is produced at ambient temperature under normal atmospheric pressure. It has been demonstrated that cold plasma inactivates pathogenic and spoilage microorganisms on various foods and surfaces (Bourke et al. 2018). Factors affecting the efficacy of cold plasma include generating device, power input, mode of exposure, exposure time, feeding gas or atmosphere composition, temperature, and relative humidity. Due to the nature and versatility of cold plasma, the mechanisms for its effects on fresh produce are rather complex. Its impact is related to cold plasma-induced reactive species, change in pH, UV light, formation of oxidative compounds (O_3, H_2O_2 etc.) and the interactions of all above entities.

Cold plasma has been reviewed as a novel decontamination technology for fresh and fresh-cut produce (Niemira 2012; Mir, Shah, and Mir 2016; Misra 2016; Bourke et al. 2018; Pankaj and Keener 2018; Pankaj, Wan, and Keener 2018). Table 5 summarizes recent studies on cold plasma effects on quality of fresh and fresh-cut produce. Studies have demonstrated that cold plasma has no or limited negative impact on sensory or nutritional quality attributes of fresh and fresh-cut produce while reducing populations of pathogenic and spoilage microorganisms and extending shelf-life of fresh and fresh-cut produce.

Cold plasma can be used to treat fresh and fresh-cut produce inside sealed packages (Misra et al. 2019). For example, an in-package dielectric-barrier discharge (DBD) system (called PlasmaLabel) was able to produce more than 1,000 ppm of ozone inside sealed package containing cherry tomatoes within 1 min of treatment (Fan et al. 2012). The system achieved more than 4 log reductions of *L. innocua* and 2–3 logs reductions of *Salmonella* and *E. coli*. No negative effects on tomato color or texture were observed during a 22-day post-treatment storage at 10 °C. Similarly, in-

Table 5. Effects of Cold plasma on quality attributes and microbial populations of fresh and fresh-cut produce.

Treatment conditions (concentration, time, intensity, dose etc.)	Type of fresh produce	Effect on quality	Reference
Atmospheric cold plasma treatment (100 kV for 150s in stationary or continuous mode)	tomato	achieved greater than 5 log reductions of *E. coli* population density surface attached on tomatoes and a maximum of 3.5 log unit reduction for *L. innocua* with no significant difference in color, firmness, pH, or total soluble solids was observed between control and treated samples	Ziuzina et al. 2016
Cold plasma (400 W or 900 W for 10min)	lettuce	inhibited *E. coli* O157:H7 and S. Typhimurium by up to 2.8 log without loss of physicochemical or sensory properties	Song et al. 2015
Dielectric barrier atmospheric cold plasma (34.8 kV at 1.1 kHz for 5 min)	romaine lettuce	reduced the initial counts of *E. coli* O157:H7 and total aerobic microorganisms by ∼1 log (CFU•g^{-1}) without significantly affecting the color, CO_2 generation, weight, and surface morphology	Min, Roh, Boyd, et al. 2017
Dielectric barrier atmospheric cold plasma (42.6 kV, 10 min)	bulk romaine lettuce	reduced the population of *E. coli* O157:H7 in the leaf of the 1, 3, and 5-layer configurations by 0.4–0.8 log (CFU•g^{-1}) lettuce and DACP did not significantly change the surface morphology, color, respiration rate, or weight loss of the samples	Min, Roh, Niemira, et al. 2017
Plasma 20 W for 1 min	fresh corn salad	maintained quality and inactivated *E. coli* by 4 log	Baier et al. 2013
Atmospheric cold plasma (47 kHz, 549 W for 15,30,45,60,90,120 s)	blueberry	treatments longer than 60 s resulted in significant reductions in firmness and the surface color measurements were significantly impacted after 120 s for the L* and a* values and 45 s for the b* values	Lacombe et al. 2015
plasma processed air (2.45 GHz, 1.2 kW for 0, 2.5, 5, 7.5, 10 min)	fresh cut apple and potato	for 10 min treatment time, polyphenol oxidase and peroxidase activities were reduced by about 62% and 77% and about 65% and 89% in fresh cut apple and potato tissue, respectively, the pH value on the tissue surface dropped to 1.5 while cell integrity and dry matter content were not significantly affected	Bußler et al. 2017
Microwave plasma processed air (2.45 GHz ignition for 7 s, treatment time for 51,015 min)	lamb's lettuce, carrot, apple, and strawberry	achieved more than 6 log microbiological load with little effect on texture, odor and appearance	Schnabel et al. 2015
microwave-powered cold plasma (He and He-O_2 mixture 827 W for 9 min), He 900 W for 10 min	cherry tomato	*Salmonella* was reduced by 3.5 log with no change on the skin morphology or respiration rate	Kim and Min 2017
Atmospheric pressure cold plasma (3.95 kV up to 12.83 kV, 30s-10min)	tomato, carrot, and lettuce	disinfected microorganisms without change on fruit color	Bermúdez-Aguirre et al. 2013
atmospheric cold plasma (15 kV for 15 and 30 min)	radicchio	remained antioxidant capacity	Pasquali et al. 2016
Plasma jet for 3,5,7,9,10 and 11 min	fresh or dry walnut	remained antioxidant capacity	Amini and Ghoranneviss 2016
atmospheric cold plasma 60 kV 50 Hz for 5 min,	strawberry	reduced microflora with slight effect on respiration rate and color and firmness	Misra, Patil, et al. 2014, 2015
30 kV RMS voltage, 30, 60, 180 and 300 s	cherry tomato	weight loss, pH, and firmness for control and treated cherry tomatoes were insignificant toward the end of storage life. Changes in respiration rates and color were not drastic.	Misra, Keener, et al. 2014
In-package nonthermal plasma 60, 70 and 80 kV and treatment durations ranging from 1 to 5 min	strawberry	degraded pesticides	Misra, Pankaj, et al. 2014
in-package treatment with modified atmosphere by cold plasma	strawberry	higher firmness	Misra, Moiseev, et al. 2014
60, 80 kV for 1, 5 min.	strawberry	degraded ascorbic acid and stable anthocyanins content slightly from strawberry	Misra et al. 2015
12.5 kHz 30 (15 min for each side) and 60 min (30 min for each side)	watermelon	delayed growth of spoilage mesophilic and psychrotrophic microflora and slightly affected titratable acidity, soluble solid content, dry matter, color, and texture during storage	Tappi et al. 2016
10, 20 and 30 min (for 2 sides)	fresh-cut 'Pink Lady' apple	inhibited browning, decreases polyphenol oxidase activity and slows down metabolic rate	Tappi et al. 2014
Tea: water (g•ml^{-1}) 2.5–10.0% combine cold plasma (20, 40 W for 60s)	fresh-cut dragon	enhanced antibacterial activity of green tea extract, increase total phenolic content, and extended 3-fold shelf life	Matan et al. 2015

(*continued*)

Table 5. Continued.

Treatment conditions (concentration, time, intensity, dose etc.)	Type of fresh produce	Effect on quality	Reference
20 and 40 min (for 2 sides)	kiwifruit	maintained color, texture, and antioxidant activity	Ramazzina et al. 2015
treated for 45 s with hydrogen peroxide (7.8%) aerosols activated by atmospheric cold plasma followed by additional 30 min dwell time	grape tomato, baby spinach and cantaloupe	inactivated human pathogens by up to 4.9 log CFU/piece with slight effect on color and texture	Jiang et al. 2017
60 s at a fixed power (8 W) and 5 L•min^{-1} of argon mixed with 0.1% oxygen	corn salad, cucumber, apple, and tomato	reduced *E. coli* DSM 1116 by up to 4.7 ± 0.4 log	Baier et al. 2014
Plasma processed air treatment for 2.5, 5, 10min	apple, carrot, tomato and cucumber	10 min treatment reduced inoculated *E. coli* by 4.6 ± 2.0 and 6.0 ± 0.8 log cycles on apples and carrots, respectively, however, significant effects were found on color of tomatoes and carrots, and on chlorophyll fluorescence parameters of cucumbers	Baier et al. 2015
clove oil (1 mg•mL^{-1}, 2 mg•mL^{-1} and 4 mg•mL^{-1} 30 min) and cold nitrogen plasma (400 W 3min for 2 sides)	lettuce	synergetic antibacterial efficacy against *E. coli* O157:H7 biofilms but with mild effect on sensory quality	Cui et al. 2016
non-thermal plasma-activated water for 0.5, 2, or 5 min	Chinese bayberry	0.5min achieved a maximum reduction of 1.1 log CFU/g both for bacteria and fungi and reduced decay and improved firmness, color and total soluble solids	Ma et al. 2016.
Atmospheric air DBD (Dielectric barrier discharge) plasma discharge system (36V, 1.8A) plasma treatment for 0, 2, 4, 6, 8 and 10 min	blueberry	Populations of bacteria and fungi decreased by 93.0%and 25.8%, respectively in the 10 min group, and the blueberry decay rates reduced by up to 17.7%. Contents of sugar, vitamin C, and total anthocyanin as well as the superoxide dismutase activity level showed the maximum increases of 1.5-fold, 1.5-fold, 2.2-fold, and 79.3% in the plasma treatment groups of 6, 8, and 10 min, respectively, after 20 days of storage.	Dong and Yang 2019
dielectric barrier discharge plasma at 45 kV for 1 min	strawberry	promoted the accumulation of total phenolics, total flavonoid, anthocyanin, maintained the texture properties and inhibited microbial growth	Li et al. 2019
60, 80, and 100 kV (60 Hz frequency) for 1, 2, 3, 4, and 5 min	fresh-cut carrot	100 kV for 5 min reduced about 2 log in total aerobic mesophiles, and yeast and mold, minor changes in pH, color, texture, and total carotenoids.	Mahnot et al. 2020

package treatment of cherry tomatoes with high-voltage DBD system for 50 s achieved greater than 5 log reductions of *E. coli* populations on tomatoes and a maximum of 3.5 log unit reduction for *L. innocua* with no significant difference in color, firmness, pH, or total soluble solids observed between control and treated samples (Ziuzina et al. 2016). The treatment produced 450–900 ppm of ozone inside the packages. Furthermore, the in-package DBD treatment system was effective against *L. innocua* inoculated on strawberries, with 3.8 log reductions achieved. No significant impact on color, firmness, pH or total soluble solids was observed (Ziuzina et al. 2020). However, the in-package treatment slightly degraded ascorbic acid and anthocyanins content of strawberry (Misra et al. 2015).

The reductions of pathogenic bacteria were frequently less on fresh-cut produce than on whole fruits with smooth surface. For example, cold plasma treatment reduced populations of inoculated *E. coli* O157:H7 and *Salmonella* Typhimurium on fresh-cut lettuce by up to 2.8 log (CFU•g^{-1}) without loss of physicochemical or sensory properties (Song et al. 2015). Dielectric barrier atmospheric cold plasma (DACP) reduced the initial counts of *E. coli* O157:H7 and total aerobic microorganisms by only approximately 1 log (CFU•g^{-1}) without significantly affecting the color, CO_2 generation, weight, and surface morphology of fresh-cut Romaine lettuce during storage (Min, Roh, Boyd, et al. 2017). The reductions of *E. coli* O157:H7 populations on romaine lettuce leaves with a 5-layer configuration in a package were only 0.4–0.8 log CFU per piece of lettuce without significant changes on the surface morphology, color, respiration rate, or weight loss of the samples (Min, Roh, Niemira, et al. 2017).

Although fresh and fresh-cut produce treated with cold plasma in general maintains its quality during post-treatment storage, too long or severe treatment of fresh produce with cold plasma can cause damages to fresh produce. For example, cold plasma significantly reduced anthocyanin content, firmness, and color parameters (L* and a* values) of blueberries after 90, 60, and 120 s treatments, respectively (Lacombe et al. 2015). However, another study (Dong and Yang 2019) showed that DBD cold plasma increased anthocyanin content of blueberry by up to 79.3%, possibly due to increased extraction efficiency of anthocyanin.

It has been shown that cold plasma impacts some enzyme activities. For example, polyphenol oxidase activity was reduced by about 62% and 77% in fresh cut apples and

Table 6. Comparison of non-thermal processing technologies: mechanism, penetration ability, potential quality damages and challenges for commercialization.

Technology	Pathogen inactivation mechanism	Penetration ability	Potential quality deterioration	Challenges for commercialization
Ionizing irradiation	Radicals and reactive species from radiolysis of water	High (gamma and X-rays)	Softening, vitamin C loss	Consumer acceptance
UV/pulsed light	DNA damage	Surface	Surface browning	Limited penetration
Ultrasound	Membrane damage	Surface	Softening	Prorogation of ultrasound in large scale
High hydrostatic pressure	Cavitation	Penetration	Softening	Tissue damage, cost
Cold plasma	Radicals and reactive species	Surface	Surface discoloration	Limited research, regulatory approval

potato tissue, respectively, following exposure to plasma processed air for 10 min (Bußler, Ehlbeck, and Schlüter 2017); peroxidase was even less stable and reduced by about 65% and 89% in fresh cut apple and potato tissue, respectively. The pH value on the tissue surface dropped to 1.5 while cell integrity was not significantly affected (Bußler, Ehlbeck, and Schlüter 2017). The decrease in pH was probably due to the formation of acidic chemical species such as HNO_3, and ONOOH (Pan, Cheng, and Sun 2019). The decreased surface pH and reduced activity of the enzymes led to slower tissue browning (Tappi et al. 2014).

Cold plasma can be combined with other antimicrobials to achieve higher reductions of pathogen. Treatments with cold nitrogen plasma and clove oil resulted in synergetic antibacterial efficacy against *E. coli* O157:H7 biofilms on lettuce. However, the appearance and overall acceptability of the treated lettuce were lower than the nontreated samples (Cui, Ma, and Lin 2016). Cold plasma was also used to activate (ionize) hydrogen peroxide aerosol by passing aerosolized hydrogen peroxide through plasma field (Song and Fan 2020). The combined treatment significantly ($P < 0.05$) improved the efficacy of aerosolized hydrogen peroxide against *Salmonella* and *L. innocua* on tomatoes, apples, cantaloupe, and Romaine lettuce. Firmness and color of treated samples (tomato, baby spinach and cantaloupe) were not significantly affected (Jiang et al. 2017). Research also showed that cold plasma could enhance antibacterial activity of green tea extract on fresh-cut dragon fruit (Matan et al. 2015).

Plasma activated water, obtained from treatment of water with cold plasma, has been applied as a wash to treat fresh and fresh-cut produce. Reactive species produced from oxygen and nitrogen in air by cold plasma are dissolved in water, and reactive species in water along with low pH have antimicrobial activities against various bacteria (Thirumdas et al. 2018; Xiang et al. 2019). Washing fresh-cut pears with plasma-activated water for 5 min significantly reduced the growth of native microbiota on fresh-cut pears during a 12-day storage at 4 °C, and did not affect soluble solid content and titratable acidity (Chen et al. 2019). However, the presence of organic and inorganic materials leached from fresh-cut produce may reduce the efficacy of plasma activated water against bacteria when used for commercial application.

Cold plasma is an emerging technology that has a potential to be used to mitigate the risk of pathogen contamination without significant effects on product quality of fresh and fresh-cut produce. However, studies conducted so far have been performed mostly in the lab-scale, where only a few pieces of fresh produce are often treated. When scaled up, the technology will likely have limited effectiveness on human pathogens present on fresh produce. The technology needs to be validated in pilot scale and commercial trials. Some other limitations of cold plasma technology are the extended treatment times and the need for the sample to be in proximity to the plasma source for certain types of cold plasma applications. Despite such limitations, there is a potential for plasma being incorporated into packing line of fresh-cut produce processing facilities. Specifically, cold plasma can be combined with modified atmosphere packaging to maintain the quality of fresh-cut produce during post-treatment storage (Misra, Moiseev, et al. 2014). Super atmospheric oxygen packaging in which packages are flushed with high oxygen may be used to promote the efficacy of cold plasma treatment because high amount of reactive species is produced in presence of high oxygen levels.

Considerations for commercialization and research directions

Fresh and fresh-cut produce provides consumers convenience and health benefits, meeting the changes in lifestyle and the demands for healthy foods. However, outbreaks of foodborne diseases have been associated with these products in recent years. Several non-thermal physical technologies have been developed and evaluated on fresh and fresh-cut produce to minimize the risk of human pathogen contamination. It is obvious that each of the technologies has its own challenges for commercial applications, such as limited antimicrobial efficacy, undesirable changes in product quality, requirement of regulatory approval, and reluctance in consumer acceptance (Table 6). Regarding regulatory approval, all physical interventions discussed in this review except cold plasma have been approved by U.S. regulatory agencies for use on fresh and fresh-cut produce, although there are restrictions in terms of dose, intensity, types of fresh produce, and purposes of use. As outbreaks of foodborne illnesses associated with fresh produce occur every year, it is important to continue research on microbial inactivation technologies, which may eventually be applicable to the produce industry to market safer fresh produce (Julien-Javaux et al. 2019). To facilitate the commercialization of the technologies, cost analysis, sustainability, and consumer education should also be considered. For example, ionizing radiation is very effective in reducing populations of fresh produce and has been approved for use on some fresh and fresh-cut produce, however consumers are reluctant to accept the technology due to misconception of the technology. In addition, some technologies such as cold plasma are still in an early stage of development and only laboratory scaled experiments are conducted. Therefore, optimization and industrial scale trials are required before being considered for commercial trials. In addition, possible formation of chemical byproducts needs to be evaluated for regulatory approval. Moreover, one technology may not be effective enough in inactivating human pathogens without causing changes in various quality attributes. Therefore, combinations of technologies with other treatments may be desirable. Finally, to develop intervention technologies that address the microbial food safety issues associated with fresh and fresh-cut produce, it is clear that a multidisciplinary strategy is needed that involves microbiology, engineering, food quality, and postharvest biology.

Conclusion

This article reviews recent developments in the technologies with a focus on their impact on quality attributes of fresh and fresh-cut produce. Ionizing radiation at doses of 1 or 2 kGy does not significantly impact the quality of most fresh and fresh-cut produce items. Yet, the commercial application of the technology is very limited partially due to the reluctance in consumer acceptance. UV-C and pulse light exhibit some quality benefits, such as increasing antioxidants. However, owing to their low penetration, it is difficult to significantly reduce populations of pathogens on all surfaces of fresh produce. While ultrasound may enhance the antimicrobial efficacy of aqueous sanitizers, the efficacy is rather limited, often achieving about 1 log reductions of common pathogenic bacteria and causing quality deterioration. While high hydrostatic pressure has been studied on fresh and fresh-cut produce demonstrating that high pressure (>300 MPa) significantly inactivates pathogenic bacteria, though product quality, especially firmness, is compromised. In addition, whether high pressure-treated products can be regarded as fresh produce is debatable. Cold plasma is an emerging technology showing limited effectiveness on quality while achieving significant reductions of human pathogens. Much more research is needed before being considered for commercial application. Overall, there are a number of physical technologies that can enhance microbial safety of fresh and fresh-cut produce. However, each of the technologies has limitations and further research is needed to minimize quality loss, while maximizing antimicrobial efficacy.

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