



Role of Ozone in Post-Harvest Disinfection and Processing of Horticultural Crops: A Review

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ABSTRACT

Consumers' awareness toward nutritionally superior foods and improved knowledge of human health have enhanced the inclusion of fruits and vegetables as an integral part of regular dietary intake. However, concerns regarding the safety and quality of foods especially with reference to the outbreak of foodborne illnesses cause a major complication in the consumption of fruits and vegetables. Other major concerns, besides the safety of food from foodborne pathogens, include spoilage due to microbes and chemical pesticide residues. Traditionally, fresh fruits and vegetables are sanitized using chemicals, viz., chlorine, peracetic acid, electrolyzed water, hydrogen peroxide, etc. All these chemicals have been proven to exhibit ill effects over the consumers and the environment over a period of time, and thus, there is a great need for a safe alternative technique, which is eco-friendly and sustainable industrially. Ozone treatment is one such green technology available with multiple benefits such as antimicrobial nature, shelf life extension, pesticide residue removal, starch modification, waste water treatment, and many other industrial applications. It was also approved by FDA as a Generally Recognized As Safe (GRAS) sanitizer because of its eco-friendly nature (degradation into nonharmful oxygen after a short half-life) in addition to its inherent antimicrobial and antiethylene activity. This review focuses on ozone, its mode of action, and its applications in different horticultural crops with potential industrial use.

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Introduction

In the recent past, consumption of horticultural commodities such as fruits and vegetables has increased considerably from 60.3 to 72.9% (by mass) with the significant growth in family income (Ansai and Wambogo 2021). Further consumers are becoming aware of the ability of horticultural produce in fighting chronic diseases, viz., cardiovascular diseases, cancer, diabetes, and obesity (Kalpourtzidou, Eilander, and Talsma 2020). Hence, with the increasing demand for fresh fruits and vegetables, there are constant innovations in their production technologies, resulting in surplus production. However, a huge proportion of fresh fruits and vegetables are being disposed off at various stages of production starting from farmer's field to the end consumer plate (Pandiselvam et al. 2017). Regular consumption of fruits and vegetables has been proven to reduce the risk of certain noncommunicable diseases such as cardiovascular diseases and certain kinds of cancer; additionally, they assist in prevention of weight gain and ultimately reducing the risk of obesity (Hartley et al. 2013). Horticultural commodities are well-

appreciated due to their pleasing sensory characteristics contributed by their taste, aroma, texture, color, gloss, and shape.

Consumers around the globe pay a great deal of attention to the appearance or color of these products. However, their limited shelf life and microbial quality are of major concern, as a large number of foodborne illness outbreaks had been associated with the consumption of these produce (Denis et al. 2016). Thus, the major focus has been on the technologies to eradicate the incidence of foodborne illness triggered by food pathogens, chemicals, and waste water. Traditionally, water with dissolved sanitizers, viz., chlorine, peracetic acid, electrolyzed water, hydrogen peroxide, etc. is being used for washing fresh fruits and vegetables. Chlorine water, being the most widely used sanitizing solution around the world, has limitations in killing the microbes present over the surface of fruits/vegetables. Chlorine provides a maximum of 1 or 2 log reduction within the permitted limits, but their residual by-products have negative effects on the environment and human health (Pandiselvam et al. 2017; Sarron, Gadonna-Widehem, and Aussenac 2021).

With the increased awareness of the consumers regarding the ill effects of these synthetic additives on health and environment, the use of these additives in food products was restricted in a few developed nations (Ma et al. 2017). Chlorine is known to react with organic matter, bromides, and iodides in the waste water to form harmful toxic compounds, *viz.*, brominated and iodinated disinfection by-products (Shen et al. 2016; Yang et al. 2014). Thus, there is a great concern for developing novel alternative green technologies for preserving the safety and quality of horticultural commodities such as fruits and vegetables. Hence, considering the extant technologies for disinfecting food products, ozone treatment appears to be the most relevant technique, which is gaining greater momentum in the horticultural industry (Miller, Silva, and Brandão 2013; Pandiselvam et al. 2020, 2017).

Ozone is a triatomic molecule of oxygen (O_3) with high reactivity. It reacts rapidly with the targeted microbes/organic debris due to its greater oxidative potential and decomposes instantaneously into diatomic harmless oxygen (O_2) molecules (Pandiselvam et al. 2019; Raghunathan et al. 2021; Sivaranjani et al. 2021). Traditionally, it is being used for decontaminating drinking water supplied by municipalities, industrially processed water, bottled drinking water, and water in swimming pools. However, recently, this safe disinfection treatment has been adopted widely in the treatment of industrial effluent, medical water/instruments, industrial process equipment, aquaculture units, water recreation parks, and private and public spas (Pandiselvam et al. 2020).

The sanitizing power of ozone is optimum in the range of 0.5–2.0 ppm. As it is sparingly soluble in water at 20 °C, it requires to be efficiently dispersed for achieving required antimicrobial activity. In general, ozone has been proven to exhibit antibacterial, antifungal, antiprotozoan, and antiviral activities (Kaavya et al. 2021; Niveditha et al. 2021; Pandiselvam et al. 2020, 2017) relatable to fresh horticultural produce and their products. Wani et al. (2015) reported efficacy of ozone against certain Gram-positive and Gram-negative bacteria along with some other pathogenic microbes. Additionally, it was also found to effectively degrade mycotoxins and arrest pest infestation during storage (Sujayasree et al. 2021). The sanitizing effects of ozone remain undisturbed when the pH of water is in the range of 6.0–8.5. The major advantage with ozone treatment is that its half-life is very low, *i.e.*, about 20 minutes, and leaves no residues in the fruits/vegetables after that period. However, it is known to generate few partly oxidized complexes on reaction with certain organic

compounds and they may persist in the produce. Ozone is found to be extremely corrosive to equipment and fatal to human beings at concentrations greater than 4.0 ppm for prolonged periods. Humans can detect the ozone concentrations in the range of 0.01 to 0.04 ppm due to sensitive olfactory sensors. Ozone was found to exhibit a pungent unpleasant odor at 1.0 ppm and irritates eyes and throat (Reddy, Rao, and Sharma 2017). Thus, when used with appropriate caution, this ozone technology has the potential to cater the needs of the horticultural industry. This review discusses the prospects of ozone as a potent disinfectant agent for various horticultural commodities.

Mode of action

Ozone oxidizes various microbial cellular components and chemical compounds characterized with double bonds, sulfhydryl groups, and phenolic rings. Thus, ozone targets the genetic material of the microbes, phospholipids present in their membranes, and intracellular enzymes. All these reactions lead to the destruction of microbial cells and ultimately their death. Since the ozone molecules are highly unstable in gaseous and solution form, it decomposes into free radicals with high oxidizing power/reactivity, *viz.*, hydroxyl ($^{\circ}OH$), superoxide ($^{\circ}O_2^-$), and hydroperoxy ($^{\circ}HO_2$) radicals (Manousaridis et al. 2005).

The complex process of microbial inactivation by ozone involves its action on various cell membranes and their constituents (fatty acids) along with cell components (enzymes and nucleic acids). Bacteria are single-celled microbes with a strong cell membrane. Ozone acts on these microscopic organisms by hampering their cellular metabolism through inhibition/blockage of enzyme systems. Adequate quantities of ozone break through their cell membrane, resulting in their inactivation/destruction. The mechanism by which ozone annihilates the target microbes could be explained in two ways: (i) the proteins, peptides, and other amino acids of vital enzymes are broken into smaller peptides through the oxidation process and (ii) the polyunsaturated fatty acids are oxidized to acid peroxidases (Chen et al. 2007). Harmful microbes are deactivated by disruption of plasma membranes or by the process of cell disintegration (Figure 1). Ozone was also shown to effectively deactivate the bacterial spores, *viz.*, *Bacillus* sp. Transmission Electron Microscopy (TEM) studies indicated that ozone acts on the outer component of the bacterial spores, which constitutes 50% of spore volume and ultimately results in exposing the sensitive cortex and core components to ozone (Khadre, Yousef, and Kim 2001). Young and Setlow (2004) hypothesized that

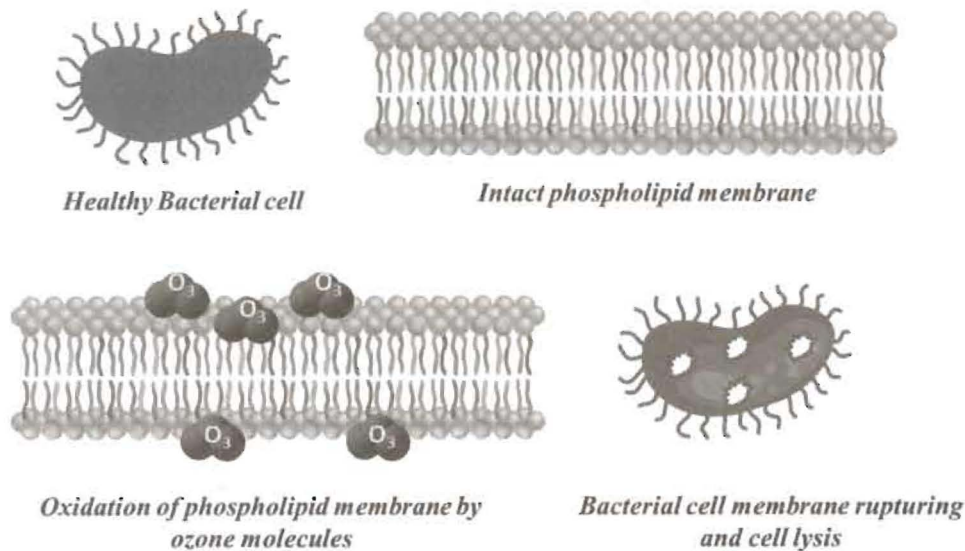


Figure 1. Mechanism of bacterial cell lysis induced by ozone oxidation reactions.

ozone acts by destroying the germinability of the microbial spores rather than directly killing through DNA oxidation/mutation. Researchers have further proved the damage caused to inner components of spores (cortex and core) by rupture that negatively influenced the germination.

The antimicrobial activity of ozone is ascribed to its direct (ozone molecule) and indirect (free radicals) mechanisms. At times, the free radicals are observed to exhibit greater oxidation potential than the molecular ozone. Although both the oxidation reactions (direct and indirect) occur simultaneously, one of them would dominate based on certain controlling factors such as composition, pH, and temperature of the solution/medium (Ozkan, Smilanick, and Karabulut 2011). The disruptive action of ozone through oxidation is far quicker than with other disinfectants having similar mode of action, *i.e.*, their permeation through the cell envelopes for effective rupture (Pascual, Llorca, and Canut 2007). With respect to the range/spectra of antimicrobial action, there is a huge variation based on their inherent sensitivity to the oxidation process. For example, yeast and fungi exhibit considerable resistance compared to the bacteria. Similarly, Gram-negative bacteria exhibit greater tolerance to ozone compared to Gram-positive bacteria. Because of this special mode of action, wherein ozone kills the microbes through cell disruption, no resistance has been developed by microbes so far to ozone (Rojas-Valencia 2011).

Ozone is also known to deactivate enveloped and nonenveloped viruses present in water (Blanchard et al. 2020). Basically, viral particles are of miniscule nature and made up of crystals/protein coats and some macromolecules. Contrary to other microorganisms, these viral particles proliferate by hijacking and transforming the host

cell proteins. Higher doses of ozone have the ability to destroy the viral protein shells/capsid through the oxidation process, thus exposing their sensitive genetic material (DNA/ RNA) for destruction. Research over the years has explored the efficacy of ozone against various bacteriophages, enveloped viral species like influenza A virus, bovine rhinotracheitis virus, vesicular stomatitis virus, and nonenveloped viruses, *viz.*, canine hepatitis virus, polio type I *etc.* (Dubuis et al. 2021). Similarly, Blanchard et al. (2020) have reported that virus particles without lipid coatings are found to be relatively less susceptible to ozone than the enveloped ones.

The action of ozone on hydrocarbons resulted in the formation of carboxyl and carboxyl oxides. Carboxyl oxide is a criegee intermediate, which is either isomerized into keto-hydroperoxide or decomposes to hydrocarbonic acid. During ozonolysis of ethylene, ozone cleaves the double bond of ethylene and forms an unstable cyclic primary ozonide, *i.e.*, 1,2,3-trioxolane, which quickly gets transformed into formaldehyde (HCHO) and an unstable hydroperoxyacetaldehyde (CH_2OO^*). With prolonged ozonolysis, the hydroperoxyacetaldehyde might recombine with formaldehyde to form secondary ozonide—an isomer of primary ozonide, *i.e.*, 1,2,4-trioxolane or decomposes to form free radicals and carbon gases (Alam et al. 2011) (Figure 2).

Beneficial effects of ozone

Effect of ozone on pathogenic and spoilage microorganisms

Generally, fruits and vegetables are consumed raw or as minimally processed products (fresh-cut fruits/salads) by a large segment of consumers. As they are loaded with

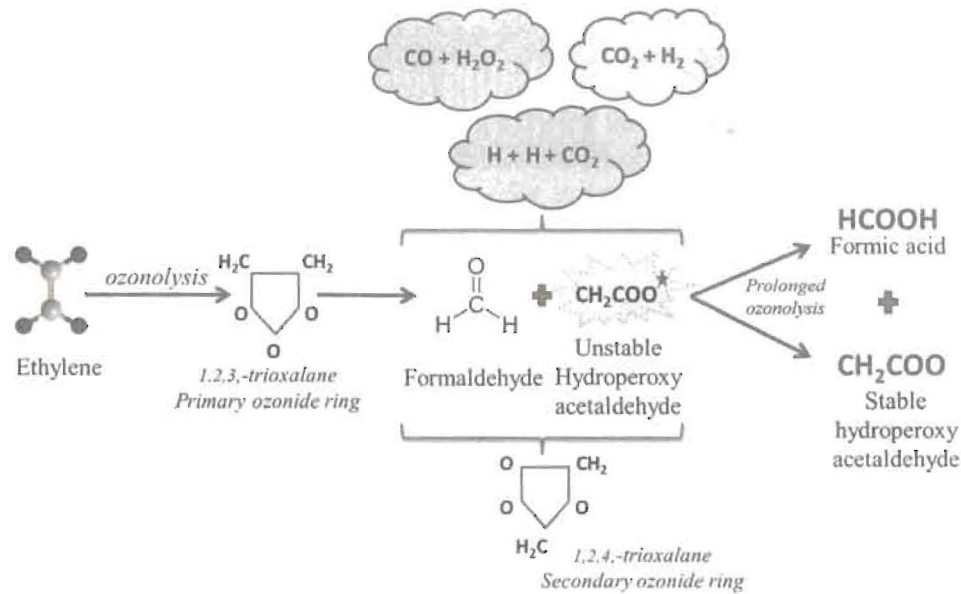


Figure 2. Illustration depicting ozonolysis of ethylene molecules.

various kinds of microbes during the journey from the field to end consumers, there are greater chances for foodborne pathogen outbreaks. The most commonly encountered microbes include mesophiles, coliforms, mold, and yeast (Bintsis 2018). These food safety microbes are reported to be present in the concentrations ranging from 10^3 to 10^9 CFU/g.

The disinfection property of ozone toward various foodborne pathogens was primarily reported during 1873 by Benjamin Cornelius Fox, a renowned chemist of Britain (Bialoszewski et al. 2010). Ozone, in both forms (gaseous as well as aqueous), was known to effectively inactivate most of the human and food safety-related pathogens, viz., *E. coli*, *Listeria*, *Salmonella*, *Staphylococcus*, *Campylobacter*, *Pseudomonas*, *Aspergillus*, *Brettanomyces*, *Trichophyton*, *Bacillus*, Adenovirus, and Norovirus (Table 1). Various factors such as the nature of fruits/vegetables, initial load of the pathogen, the conditions of incubation, ozone concentration, method of application (gas/ aqueous), duration of exposure, and water temperature are known to affect the efficacy of ozone treatment (Pandiselvam et al. 2017, 2019).

The bacterial spores possess greater resistance to ozone compared to their vegetative forms (Khadre, Yousef, and Kim 2001). Likewise, the vegetative cells of bacteria in the stationary phase are more resistant to ozone than those in the exponential phase (Cebrián, Mañas, and Condón 2016). The spores of *Bacillus stearothermophilus* are known to exhibit maximum resistance and are hence considered as indicator microbes for checking the efficacy of ozone treatments (Khadre and Yousef 2001).

Corona-Vasquez et al. (2002) reported 90% deactivation of *Cryptosporidium parvum* (protozoan parasite) with 1 ppm ozone in aqueous form for 5 minutes. Although the oocysts of *C. parvum* are resistant to chlorinated water, initial exposure to ozone in aqueous form has rendered them susceptible. Likewise, coupling of ozone treatment with water filtration could lessen the demand for ozone in organic debris-rich water to improve its quality for recycled use (Zucker et al. 2015).

Ozone was proven to be fatal against the vegetative cells of bacteria, viz., *E. coli*, *B. cereus*, and *B. megaterium* at lower concentrations (0.12–0.19 ppm) with a contact period of 5 minutes. However, the organic matter present in water renders the treatment ineffective due to its interference (Broadwater, Hoehn, and King 1973). Ozonated water also killed spoilage causing microorganisms such as *Pseudomonas aeruginosa*, yeast, *Zygosaccharomyces*, bacilli, fecal contaminants, *Enterococcus faecalis*, and food-borne pathogens such as *Listeria monocytogenes*, *Yersinia enterocolitica*, and *Staphylococcus aureus* (Akbas and Ozdemir 2008). Typically, ozone could cause 5–7 \log_{10} reduction of viable cells if there is no interference by the organic matter in aqueous media. The ozone has varying degrees of inactivation potential depending on the microbes. However, the efficacy of oxidizing properties of ozone toward the microorganisms gets reduced when the organisms remain adhered to fruits/vegetables. This adherence of microorganisms on the food product was known to reduce their viability by 1 \log_{10} compared to the control situation. Karaca and Velioglu (2014) inoculated lettuce, spinach, and parsley with *Escherichia coli*

Table 1. Effect of ozone on pathogenic and spoilage microbes present in horticultural produce.

Crop/Product	Pathogen/Disease	Ozone treatment	Response	Reference (s)
Apple cv. golden delicious	<i>E. coli</i> O157:H7 and <i>L. monocytogenes</i>	Aqueous ozone (3 mg l ⁻¹)	Significant reduction in microbial populations	Rodgers et al. (2004)
Apple cv. royal gala, golden delicious, and fuji	<i>Penicillium expansum</i>	Gaseous ozone (0.5 µl l ⁻¹)	Reduced losses during postharvest storage and patulin production	Yaseen et al. (2015)
Avocado	Stem end rot and Body rot	Fruit dip in 0.5 mg/L ozone.	Reduced the rots when the disease pressure is low.	Pak and Dixon (2001)
Baby carrots	<i>Escherichia coli</i>	Gaseous ozone (2.1, 5.2 and 7.6 mg l ⁻¹ , 22 °C, 80% RH, 5, 10, or 15 min)	Lethal effect toward <i>Escherichia coli</i> and exhibited log reduction from 7.8 to 1.11–2.64 log CFU g ⁻¹	Singh et al. (2002)
Blueberries	<i>Yersinia enterocolitica</i>	Aqueous ozone (1 mg l ⁻¹)	Reduced surface contamination	Crowe et al. (2007)
Carrots	<i>S. sclerotiorum</i> and <i>B. cinerea</i>	Gaseous ozone (450 or 600 ppb, 5 or 20 °C, 97% RH, 48 h)	Growth rate reduced by 53.2% with 450 ppb ozone and resulted in the decrease of the lesion size and height of aerial mycelium.	Sharpe et al. (2009)
Carrots (baby cut)	<i>E. coli</i> , <i>Listeria</i> , and <i>Salmonella</i>	Gaseous ozone (428 or 856 mg m ⁻³ , 2.5 or 5 h)	<i>E. coli</i> exhibited 1.2 log CFU g ⁻¹ reduction, while <i>Listeria</i> and <i>Salmonella</i> by 0.8 and 0.5 log CFU g ⁻¹ , respectively.	Bridges, RaneB, and Wu (2018)
Citrus	<i>Penicillium</i> rot	Low-level ozone enrichment (180–200 ppb)	Spoilage reduction of citrus fruits stored in a semicommercial environment	Metzger et al. (2007)
Citrus	<i>Penicillium digitatum</i> and <i>P. italicum</i>	Continuous ozone exposure (1.0 ppm) at 10 °C in an export container	The incidence of green and blue molds was delayed by 1 week.	Palou et al. (2001)
Date fruits	<i>E. coli</i> and <i>Staphylococcus aureus</i>	Gaseous ozone (5 ppm, 60 min.)	Reduction in total count	Najafi and Khodaparast (2009)
Fig	<i>E. coli</i> and <i>Bacillus cereus</i>	Gaseous ozone treatment (1.0–9.0 µl/L)	<i>B. cereus</i> was found to be highly sensitive to ozone initially but requires higher concentrations for effective control	Akbas and Ozdemir (2008)
Fig cv. Sarilop-Calimyrna	<i>E. coli</i> , aerobic mesophiles, yeast, and mold	Gaseous ozone treatment (5 mg/L)	Significant reduction in microbial count	Oztekin, Zorlugenç, and Zorlugenç (2006)
Fresh-cut papaya	Mesophilic & Coliform bacteria	Gaseous ozone treatment (9.2 µl/L, 20 min.)	More effective on coliform than in mesophilic bacteria	Yeoh, Ali, and Forney (2014)
Grapes	<i>Botrytis cinerea</i>	Gaseous ozone application at 5000 µl/L for 60 min	Graymold incidence reduced by 50%	Gabler et al. (2010)
Grapes cv. autumn seedless/scarlet royal	<i>Penicillium digitatum</i> , <i>P. italicum</i> , and <i>B. cinerea</i>	Gaseous ozone (200–350 µl l ⁻¹)	Inhibited the germination ability of fungal conidia. <i>Penicillium</i> species have more resistance compared to <i>Botrytis cinerea</i> . Ozone efficacy was increased at higher relative humidity	Ozkan, Smilanick, and Karabulut (2011)
Kiwifruit	<i>B. cinerea</i> causing stem end rot	Gaseous ozone (0.3 µl/L)	Delayed the occurrence of disease and reduced it by 56%.	Minas et al. (2010)
Onion	Surface fungal pathogens	50 nl/l during the day and 200–250 nl/l during the night	Decreased surface fungal infections with no effect on internal decay	Fan et al. (2001)
Papaya	Papaya rot	Gaseous ozone (500 mg/m ³) Ozonized water (1 mg/L)	Ozonized water treatment was more effective.	Bataller et al. (2012)
Potato cv. Altesse	<i>E. coli</i> O157:H7 and <i>S. enterica</i>	Aqueous ozone (1.9 mg l ⁻¹)	Supressed the growth of microbes	Selma et al. (2006)
Spinach cv. Clermont	<i>E. coli</i> and <i>Listeria</i> spp.	Gaseous ozone (1–10 µl l ⁻¹)	Bacterial populations were controlled with higher concentrations of ozone exposed for shorter periods and populations	Calatayud et al. (2004)
Strawberry	<i>E. coli</i> O157:H7 and <i>L. monocytogenes</i>	Ozonized water (3 ppm, 5 min.)	Microbial population exhibited 5 log reduction	Rodgers et al. (2004)
Tomato	<i>Botrytis cinerea</i>	Exposure to low-level ozone atmosphere (0.1 µmol mol ⁻¹)	Reduction in the development of observable lesions and multiplication	Tzortzakis, Singleton, and Barnes (2007)

and *Listeria innocua* and observed that vegetables treated with ozone exhibited 2 log reduction of *E.coli*. The microbial disinfection ability of ozone was found to be very high (up to 7 log₁₀ CFU/ml reductions) when the target microbes were adhered to nonreactive metallic surfaces, viz., stainless steel, and thus, it could be very well utilized for disinfecting the surfaces of food processing machines (Pandiselvam et al. 2019). Similarly, Rodgers et al. (2004) reported that the application of ozone to shredded lettuce reduced the *Salmonella* concentration by 5 log CFU/g. Zhang et al. (2005) reported that intact celery sticks when treated with aqueous ozone (0.18 ppm) have reduced the bacterial population by 1.69 log CFU/g and extended their shelf life for 9 days under 4 C. Likewise, minimally processed lettuce when treated with aqueous ozone (5.0 ppm) for 5 minutes was reported to reduce the population of *Shigella sonnei* by 1.8 log CFU/g (Selma et al. 2007).

Effect on postharvest physiology and shelf life of produce

The advantage of using ozone treatment for cold rooms/storage facilities could be either direct or indirect. Wherein the efficacy of ozone treatment varies to a large extent depending on its concentration, exposure time, and method of application (Pandiselvam et al. 2020). Moreover, it also depends on the inherent properties of the produce itself. The destructive action of ozone on ethylene present in air filtration systems could be directly correlated with the preservation of different ethylene sensitive commodities. There is no significant positive effect of injecting permitted levels of ozone gas into the common air of cold rooms, but it was shown to trigger the synthesis of natural plant defense substances that are proven to induce resistance against pathogens causing postharvest decay. However, exposure of the fresh fruits and vegetables to higher concentrations of ozone and/or for longer periods could damage the fruit tissues and thus ultimately affect their sensory and storage qualities (Reddy, Rao, and Sharma 2017).

The ability of ozone to trigger the genes related to senescence and self-defense or interaction with harmful reactive oxygen species and ethylene was documented (Castagna et al. 2007). Additionally, researchers have explored its potential to be used as a postharvest pre-storage treatment for fresh fruits and vegetables. However, the exact mode of action of ozone in inactivation of harmful pathogens is not yet clearly known. With the increasing use of ozone during the past few decades, it was proved to reduce the rate of respiration (Zhang et al. 2005), eliminate the harmful pathogens, promote

ethylene oxidation during storage (Skog and Chu 2001), stimulate sucrose metabolism and reduce flavor volatile production (Perez et al. 1999), trigger antioxidant production (Allende et al. 2007; Artes-Hernandez et al. 2007), and modulate the profiles of various enzymes and proteins (Baur et al. 2004; Zhang et al. 2005).

It has been hypothesized and successfully proven that the efficacy of ozone treatment for extending the shelf life/storage life of fresh fruits and vegetables, viz., apples, pears, grapes, oranges, cucumber, broccoli, and berries like strawberry and raspberry, relies on its ability to reduce the microbial inoculum and degrade the generated ethylene (Table 2) (Skog and Chu 2001). Application of aqueous ozone as a sanitizing agent for the minimally processed fruits and/or vegetables has resulted in the reduction of microbial loads along with an extended shelf life (Beltran et al. 2005aa).

Effect on nutritional and sensory quality

Horticultural commodities such as fruits and vegetables act as a major source of vital nutrients, viz., minerals and vitamins in our regular intake. Simultaneously, it is crucial to ensure that the postharvest treatments imposed for extension of shelf life/retardation of spoilage should not affect the sensory characteristics and nutritive value of the fresh produce. Hence, the investigation for unconventional decontamination technologies for fresh and minimally processed produces should analyze their effects on nutritional and sensory qualities along with their antimicrobial properties (Table 3). In general, ozone application was found to have no deleterious effects on the vital nutrients such as vitamin C and pigments such as Carotene in minimally processed vegetables except for sliced carrots (Chauhan et al. 2011). Zhang et al. (2005) reported the protective action of ozone on vitamin C content through inhibitory action over the enzyme polyphenol oxidase (PPO) and slowing down of the tissue metabolic processes. However, this action of ozone was highly dependent on the concentration and exposure period.

Ozone treatment improved the quality and storage life of blackberries and persimmon (Salvador et al. 2006). Likewise, ozone treatment delayed the fruit softening of strawberries (Nadas, Olmo, and Garcia 2003) and improved their ascorbic and fumaric acid content (Aguayo, Escalona, and Artes 2006). However, the aroma component of strawberries was significantly reduced. There were no deleterious effects of ozone on respiratory and ethylene production rates of grapes and peaches as well as on organic acid compositions of citrus and tomato fruits (Smilanick 2003). Minimally processed papaya fruits on exposure to ozone have shown

Table 2. Physiological effects of ozone treatment on fruits and vegetables during storage.

Crop/Cultivar	Ozone treatment	Storage	Result/Effect	Reference
Apple cv. Empire/ Delicious	Gaseous ozone (0.4 $\mu\text{l l}^{-1}$)	0 °C	No effect on internal ethylene production and other quality parameters, viz., TSS, acidity and texture; however, there is a significant reduction in ethylene content of storage environment	Skog and Chu (2001)
Asparagus cv. UC800	Aqueous ozone (1 mg l^{-1})	3 °C	The lignification activity was decelerated, while the enzymes, viz., ascorbate peroxidase, superoxide dismutase (SOD) reductase, and phenylalanine ammonia lyase (PAL), were sustained.	An, Zhang, and Lu (2007)
Bell pepper/ Capsicum cv. Ferrari	Gaseous ozone (0.1–0.3 $\mu\text{mol mol}^{-1}$)	14 °C	Higher concentrations promoted weight loss with no significant effects on texture and color	Glowacz et al. (2015b)
Broccoli	Gaseous ozone (0.4 $\mu\text{l l}^{-1}$)	3 and 10 °C	Significant inhibition of color transformation from green to yellow and amplified browning in its base	Skog and Chu (2001)
Broccoli cv. Everest, Regal	Gaseous ozone (200 nl l^{-1})	12 °C	No significant effect on color change, moisture loss, ethylene production rate, and rate of respiration	Forney et al. (2003)
Carrot	Gaseous ozone (1–5 mg L^{-1} , 3.9–24.1 °C, 9.5–110.5 min)	18 \pm 2 °C	Increased their shelf life for 5 days	De Souza et al. (2018)
Carrot cv. Pusa Kesar	Aqueous ozone (200 mg h^{-1})	6 °C	Reduced lignification, maintained quality, reduced respiration and ethylene production rates, levels of carotenoids and vitamin C, and oxidative enzyme activities	Chauhan et al. (2011)
Carrot cv. Sunrise	Gaseous ozone (1000 nl l^{-1})	10 °C	Reduction in firmness and sugars with increased production of stress volatiles and respiration rate	Forney et al. (2007)
Cilantro/coriander	Aqueous ozone	0 °C	Color, quality, and aroma are maintained although there is significant electrolyte leakage	Wang, Feng, and Luo (2004)
Cucumber cv. Highjack	Gaseous ozone (0.1–0.3 $\mu\text{mol mol}^{-1}$)	12 °C	Reduced weight loss and texture loss with an increase in fructose and glucose concentrations at 0.1 $\mu\text{mol mol}^{-1}$	Glowacz et al. (2015)
European pear cv. Qishui	Gaseous ozone (6.42 mg m^{-3})	Ambient	Prolonged storage life with better quality retention and induced greater antioxidant potential while repressed polyphenol oxidase (PPO) activity	Zhao et al. (2013)
Grapes cv. Thompson Seedless/Flame Seedless	Gaseous ozone (0.3 $\mu\text{l l}^{-1}$)	5 °C	Amplified physiological loss in weight and no phytotoxic injuries	Palou et al. (2002)
Highbush blueberries cv. Coville	Gaseous ozone (700 nl l^{-1})	0 °C	Increased storage life, stimulated respiration and ethanol production, and no phytotoxicity	Fan et al. (2001)
Highbush blueberries cv. Ozark Blue	Gaseous ozone (4.0 $\mu\text{l l}^{-1}$)	4 and 12 °C	Reduced physiological loss in weight and loss of firmness	Concha-Meyer et al. (2015)
Kiwifruit cv. Hayward	Gaseous ozone (0.3 $\mu\text{l per liter}$)	0 °C and 90–95% RH	Reduced ripening rate and blocked ethylene activity and increased antioxidant activity	Minas et al. (2012)
Lettuce	Aqueous ozone (10 mg l^{-1})	4 °C	Sustained visual quality and firmness, increased browning, and reduced rate of respiration	Beltran et al. (2005a); Wei et al. (2007)
Lettuce	Aqueous ozone (1 mg l^{-1})	10 °C	The enzymes such as pectin methylesterase (PME), polyphenol oxidase (PPO), and peroxidase were inhibited.	Rico et al. (2006)
Nashi pear cv. Anjou and Bosc	Gaseous ozone (0.4 $\mu\text{l l}^{-1}$)	0 °C	Decrease in the storage room ethylene concentration with no effect on internal ethylene, firmness, and TSS; no phytotoxicity	Skog and Chu (2001)
Onion	Gaseous ozone (50 nl/l during the day and 200–250 nl/l during the night)	0 °C	Decreased moisture loss with no significant effect on its sprout inhibition	Fan et al. (2001)
Papaya cv. Golden	Aqueous ozone (4 $\mu\text{l l}^{-1}$)	45–65 °C	No substantial variations in the wax coating and cuticular arrangement over the fruit surface	Kechinski et al. (2012)

(Continued)

Table 2. (Continued).

Crop/Cultivar	Ozone treatment	Storage	Result/Effect	Reference
Peach cv. Elegant Lady/ Zee Lady/ O'Henry	Gaseous ozone (0.3 $\mu\text{l l}^{-1}$)	5 °C	Increased PLW with no effect on rates of ethylene production and respiration. No phytotoxicity	Palou et al. (2002)
Persimmon cv. Rojo Brillante	Gaseous ozone (0.15 $\mu\text{l l}^{-1}$)	Ambient	Maintained texture, increased PLW, and electrolyte leakage from fruits	Salvador et al. (2006)
Pomegranate cv. Hicaznar	Gaseous ozone (5.2 and 10.4 $\text{mg h}^{-1}\text{m}^{-3}$)	5 °C	Suppressed stress volatiles causing off flavors and maintained low acetaldehyde	Ozon and Kafkas (2015)
Raspberries	Aqueous ozone (21 mg l^{-1} for 64 min)	-	Decrease in the storage room ethylene concentration with no effect on internal ethylene, firmness, and TSS; no phytotoxicity	Bialka and Demirci (2007)
Strawberry cv. Camarosa	Gaseous ozone (1.5 $\mu\text{l l}^{-1}$)	2 °C	Reduced PLW and fruit softening and aroma	Nadas, Olmo, and Garcia (2003)
Strawberry cv. Fengxiang	Aqueous ozone (4.3 mg m^{-3})	4 °C	Prolonged the storage life and hindered anthocyanin degradation and titratable acidity	Zhang, Xiao, and Salokhe (2006)
Sweet orange cv. Valencia/ Ovale	Aqueous ozone (0.6 mg l^{-1})	5 °C	Reduced senescence and PLW	Di Renzo et al. (2004)
Tangerine cv. Sai Nam Pung	Gaseous ozone (200 $\mu\text{l l}^{-1}$)	Ambient	Improved activities of superoxide dismutase (SOD), catalase (CAT), and ascorbate peroxidase	Boonkorn et al. (2012)
Tomato	Gaseous ozone (10 $\mu\text{l l}^{-1}$ for 10 min)	20 °C	Reduced physiological loss in weight, triggered buildup of phenolics, hindered softening, and reduced pectin methylesterase activity (PME)	Rodoni et al.(2010)
Tomato	Gaseous ozone (25, 35, and 50 $\mu\text{l l}^{-1}$)	Ambient	Delayed color change from green to red and fruit rotting	Zambre, Venkatesh, and Shah (2010)
Zucchini cv. Prometheus	Gaseous ozone (0.1–0.3 $\mu\text{mol mol}^{-1}$)	8 °C	Reduced physiological loss in weight at 0.1 $\mu\text{mol mol}^{-1}$ and texture loss	Glowacz et al. (2015)

a decline in vitamin C content by 2.3%, while the total phenolics were increased by 10.3% compared to that of untreated control fruit (Yeoh, Ali, and Forney 2014). However, a few researchers have reported the increased loss of moisture with the ozone treatment of fruits and vegetables (Palou et al. 2002).

Although ozone was not known to hamper the sensory quality of the fresh and fresh-cut products, higher doses of ozone treatment could alter the sensory attributes of certain produce. A noteworthy effect of ozone observed on the sensory quality of the treated product is the loss of aroma. Loss of aroma was observed in orange juice stored in cold rooms enriched with ozone gas (Pott et al. 2020), which could be attributed to the process of oxidation of volatile compounds. Apart from the visual quality, browning, texture, and aroma were the preferred parameters for testing of the sensory quality. Lettuce leaves exhibit browning on their edges and surfaces, which is directly correlated with the phenylalanine ammonia lyase (PAL) activity in general and negatively correlated with their sensory acceptability and their shelf life (Beltran et al. 2005a). However, application of ozone gas was found to be effective in reducing the lettuce leaf browning compared to traditional chlorine treatments (Olmez and Akbas 2009). This reduction of browning by ozone could be due to inhibition of browning enzymes, viz., polyphenol oxidases (PPO) and peroxidases (POD) (Liu et al. 2020). Application of ozone has successfully controlled the unwanted color change of broccoli from green to yellow (Salvador et al. 2006) with no effect on the discoloration of fruits like peaches (Panou, Karabagias, and Riganakos 2018) and vegetables like carrots (De Souza et al. 2018).

Role of ozone in processing industries

Fruit and vegetable processing

Of late, the demand for processed food products is increasing day-by-day. Ozone is one of the powerful preservative systems with broad-spectrum antimicrobial activity pertinent to fresh horticultural produce (Pandiselvam et al. 2019). Wani et al. (2015) reported the efficacy of ozone against bacteria (Gram-positive and Gram-negative), fungi, and virus. Additionally, ozone was also found to have the ability to destroy storage pests and degrade the mycotoxins. Hence, it is preferred over most of the popular disinfectants, viz., chlorine, due to inefficacy of chlorine concentrations limited by the laws of food regulation.

Ozonized water is being used normally for washing different horticultural commodities such as fruits and vegetables prior to storage (Karaca and Velioglu 2007).

Its applications are extended to minimally processed fruits and vegetables, as it aids fully in reducing the microbial populations and extending their storage life (Beltran et al. 2005a, 2005b). Reports of reduction in bacterial populations of ozone water-treated fruits, viz., grapes, blackberries, black pepper, broccoli, carrots, tomato, and shredded lettuce, were found. Fruit beverages can also be ozonized by injecting an appropriate amount of ozone into the fruit juice through an aspirator. Thus, approval of ozone as a direct food additive (FDA 2001) has led to its application in processing of various fruit juices, viz., apple juice (Cataldo 2008), strawberry juice (Tiwari et al. 2009b), blackberry juice (Tiwari et al. 2009a), orange juice (Patil et al. 2009a, 2009b; Tiwari et al. 2008), and apple cider (Choi and Nielsen 2005; Steenstrup and Floros 2004).

Wine processing

Maintenance of hygiene in wine industries is of major concern like in any other food industry. Maintenance of sterility and quality throughout the winery is of paramount importance for better wine production and sales. The major concern in the wine industry is cross-contamination with the natural/wild yeast, i.e., *Brettanomyces spp.*, which causes the wine spoilage by developing an off-flavor typically referred to as 'burnt plastic'/'wet wool'/'leathery.' Generally, these wild yeasts were found to grow in very low numbers when wine is stored in barrels/bottles for the aging process (Smith-McCollum 2007).

In winery, ozone may be used for barrel sanitization and surface sterilization of places. Considering the disinfection potential of ozone, most of the wine industries have adopted ozone treatment as a major operation in their barrel washing protocols. Although, the standard barrel washing protocols vary from winery to winery, it generally includes a hot water rinsing under high pressure followed by the application of ozonized water treatment. During ozonized water treatment of barrels, the concentration of ozone to be used and the time period of exposure are primarily determined by the level of contamination present in the barrels. For example, at 10.0 ppm, the rinse time for healthy barrel is 30 seconds and at 5.0 ppm, it would be one minute. Generally, the healthy barrels were treated with 2.5 ppm ozone for 2 minutes after hot water rinse, while a typically contaminated barrel requires 5.0 ppm treatment for the same time period (Cullen and Norton 2012). The ozonized water is being used for disinfection of a wide range of equipment and working surfaces in the wineries on a regular basis for control of

unwanted microbes and to avoid cross-contamination with wild yeast. The ozonized water could be very easily used for decontamination of walls, floor, bins, tanks, crushers, drains, and any other wettable components of a typical winery unit. In general, the winery equipment is typically cleaned in the first step followed by a final rinse with ozonized water.

Similarly, wineries are equipped with heavy machineries, which could not be separated/moved apart for regular cleaning. Thus, there is a necessity for cleaning alternatives with minimal or no residues. The principal threat in the wine making process is the cross-contamination occurring during the long production processes, which extend from harvest to tank to barrel to final bottling. The major risk is encountered during the transfer of wine between different tanks or barrels for creation of the unique blend of flavors sought in a fine bottle of wine (Cullen and Norton 2012). To mitigate this risk, most of the wineries adopt strict measures in their CIP (clean in place) protocols. In order to disinfect these tanks, pipes, hoses, bottling lines, fillers, pump systems, filters, etc., they must be cleaned-in-place with soaps, detergents, surfactants, pressurized water, and/or chemicals such as chlorine or iodophore solutions and thoroughly rinsed with hot water or steam to remove residues. For final decontamination, ozonized water is recirculated throughout the equipment using a closed loop of pipe or hose. The dispersed ozone reacts with organic material present in the equipment and disintegrates it. The use of ozonized water for the CIP process reduces expenditure and saves time with no chemical residues (Smith-McCollum 2007).

Removal of pesticide residues

Several pesticides are used for increasing the quality and quantity of various food crops. These pesticides were known to have adverse effects on the environment as well as on human beings, animals, and aquatic organisms (Ikeura, Kobayashi, and Tamaki 2011b). Also, a part of the applied pesticide remains in the harvested produce even after harvest and these residues are equally harmful when consumed by the people, and thus, the pesticide residues in the food crops have become a global concern today.

Some chronic effects of consuming pesticide residues include neurotoxicity, carcinogenesis, abnormal reproduction, and cell development (Burrows et al. 2002). Hence, the contamination by pesticide residues is a major concern for both the farmers and the consumers. There are several ways to reduce pesticide residues. For example, washing of harvested produce with

or without chlorine has shown to reduce the pesticide residues (Kaushik, Satya, and Naik 2009). Household preparations containing different proportions of vinegar, common salt, and tap water or refrigeration followed by multiple stir frying has shown to remove a major portion of pesticide residues from vegetables (Zhang, Liu, and Hong 2007). Similarly, nanofiltration (Chen et al. 2004), activated carbon filtration (Foo and Hameed 2010), reverse osmosis (Bonne et al. 2000), distillation, adsorption (Tepus, Simonic, and Petrinic 2009), photocatalytic degradation (Devipriya and Yesodharan 2005), photodegradation (Tanaka and Reddy 2002), ionizing irradiation (Basfar, Khaled, and Al-Saqer 2012), gamma irradiation, biodenitrification reactors (Aslan and Turkman 2006), electrolysis adsorption (Vlyssides et al. 2005), microwaving (Salvador et al. 2002), electrochemical oxidation (Arapoglou et al. 2003), and ozonation (Ikeura, Kobayashi, and Tamaki 2011a; Wu et al. 2007a) are few other approaches used commercially to decrease the load of residues.

Among these methods, ozonation could be the safe and promising method for cost-effective removal of pesticide residues from the perishable horticultural produce (Pandiselvam et al. 2020). The efficacy of ozonized and chlorinated water dip in the disintegration of harmful pesticides, viz., bifenthrin and deltamethrin, was reported by De Ávila et al. (2017) in fresh and processed apple fruits. Destruction of certain nutritional elements with the application of high levels of oxidants is one of the major concerns. The feasibility of using low dissolved ozone in the range of 1.4–2.0 mg/L for the elimination of some common pesticide residues, viz., diazinon, methyl parathion, parathion, and cypermethrin, from vegetable surfaces (*Brassica rapa*) was reported by Wu et al. (2007b). The same report revealed that >60% cypermethrin and 27–55% of diazinon, methyl parathion, and parathion were successfully removed from vegetables using low concentrations of ozone.

The efficacy of different wash treatments, viz., Cl, ClO₂, CH₃CO₃H, and O₃ in elimination of few pesticides such as ethylene thiourea and themancozeb from fresh and processed apples was studied by Hwang, Cash, and Zabik (2001). They found that among all the wash treatments, 3.0 ppm ozone (O₃) was found to be effective in thoroughly eliminating ethylene-thiourea (100%) and partial reduction of mancozeb by 56–97%.

The efficacy of an ozone microbubble (OMB) producer in removing the residual fenitrothion from lettuce, cherry tomatoes, and strawberries was studied by Ikeura, Kobayashi, and Tamaki (2011a). Among the two types developed, the decompression type was proved to be efficient in pesticide residue removal compared to the gas-water circulation type. This could be mainly due to

generation of a large number of smaller ozone micro-bubbles through decompression, which have the potential to permeate into the vegetables compared to the gas-water type. Additionally, OMB treatment solutions generate hydroxyl radicals that are extremely useful in disintegrating organic compounds, comprising pesticide residues (Ikeura, Kobayashi, and Tamaki 2011b; Sumikura et al. 2007; Takahashi, Chiba, and Li 2007). As most of the pesticides applied over fruits and vegetables are water soluble, cleaning with ozonized water has double benefits, *viz.*, primary removal of soil and pesticides through simple dissolution and secondary through oxidative degradation of organic residues present on their surface.

Ozone residues and their toxic byproducts

The multiple benefits of ozone have turned it to an indispensable agent in many fruit and vegetable processing industries. The most commonly used disinfectant chlorine on reacting with the organic compounds produces carcinogenic byproducts, *viz.*, trihalomethanes and haloacetic acids (Hua and Reckhow 2007), while the ozone does not produce these halogenated byproducts in water (Richardson 2003). However, little amount of halogenated byproducts are generated in the presence of high levels of bromide in water (Zhang et al. 2020). Some of the major organic byproducts associated with the use of ozone in fruit and vegetable processing industries comprise carboxylic acids, aldoketo acids, and aldehydes. Brominated byproducts have exhibited greater potential of carcinogenic and mutagenic activities, and thus, they are the only regulated byproduct from the ozone treated water (Huang, Chang, and Shih 2009; Zhang et al. 2020).

However, latest research has exposed larger carcinogenic potential of iodinated byproducts than their chlorinated and brominated analog (Plewa et al. 2004; Richardson 2003). These iodinated byproducts are formed by the reaction of iodides with the disinfectants, and their levels are very low from ozone compared to chlorine and chlorine dioxide used in conventional cleaning of horticultural processing units (Krasner 2009). Ozone was also found to possess the potential to destroy chlorine byproducts, pesticides, and other toxic organic molecules present in the treatment water without any lethal residues (Remondino and Valdenassi 2018).

Health and safety aspects of ozone

Since ozone is a noxious gas, it should be carefully supervised in the treatment plants during its usage. It is one of the most important criteria for approval of

ozone in fruit and vegetable processing units. It is essential to monitor individuals coming in contact with ozone in their workplaces. However, there were no reports of deaths due to hyperozone exposure in the past century of its industrial use. The safe limits for ozone exposure in workplaces have been set up by Occupational Safety and Health Administration (OSHA). The set limits include not more than 0.1 ppm of continuous exposure to ozone (8-hour work period) or a short-term exposure limit at 0.3 ppm ozone for 15 minutes and not to exceed more than twice per eight-hour work day (Rice 2012). In humans, ozone chiefly affects the respiratory tract. Major indications of ozone toxicity comprise headache, giddiness, a burning sensation of eyes and throat, a sharp taste and smell, and cough. Prolonged toxicity indicators are headache, paleness, memory loss, increased prevalence of bronchitis, and increased muscular excitability (Zhang, Wei, and Fang 2019).

Accordingly, ozone usage necessitates continuous monitoring in the fruit and vegetable treatment plants, if it is used for environmental/equipment disinfection. Ozone dosimeters/monitors are available, which need to be installed randomly in the treatment plants/processing units for detection of ozone in the working atmosphere. They should be equipped with suitable alarming systems so that they could warn the industrial workers once they detect a high concentration of ozone in the working atmosphere. The industry should also possess a manual/guide with all the pertinent safety information and stepwise operational instructions for working with ozonating systems (Xu 1999). The processing units should be monitored regularly for ozone off-gas, and assurance on its safe limits should be ensured. The ozone generator should be periodically checked for its calibration in terms of ozone concentration production and its flow rate. Also, they should ensure accountability of complete ozone produced by checking for leaks if any and through proper annihilation of excess ozone (Rice 2012).

When ozone is used for fumigation purposes in sanitization of godowns or cellar rooms to be used for storage of fresh fruits and vegetables, it should be carefully monitored till the far end of the room with an appropriate feedback control mechanism. However, when it is used after dissolving in water, there will always be a certain proportion of it that remains undissolved, which requires to be separated/destroyed or degassed before using the ozone dissolved water for intended purposes. This could be achieved easily with thermocatalytic ozone destruct units, which are small and efficient. If used appropriately, the ozone disinfecting systems are far safer compared to the conventional chemical (chlorine and caustics) or heat-based disinfection

Table 3. Effect of ozone on nutritional and sensory characteristics of the treated produce.

Crop/Cultivar	Ozone treatment	Storage	Result/Effect	Reference
Banana	Gaseous ozone (8 ml s ⁻¹)	Ambient	Increase in phenolics and flavonoid compounds, enriched nutritional properties, and ascorbic acid content degraded at greater concentrations/ exposure periods	Alothman et al. (2010)
Grapes cv. Autumn Seedless	Gaseous ozone (0.1 µl l ⁻¹)	0 °C	Enhanced total phenols and flavonoid content but nonsignificant in controlling fungal spoilage	Artes-Hernandez et al. (2007)
Grapes cv. Superior	3.88 g h ⁻¹ for 5 h	22 °C and 95% RH	Stimulated stilbenoid biosynthesis (trans-resveratrol and piceatannol) and viniferinas (resveratrol dehydromers and dehydrotrimers)	Gonzalez-Barrio et al. (2006)
Grapes cv. Superior seedless/Regina Victoria/ Cardinal CL80	Gaseous ozone (2 µl l ⁻¹)	5 °C	Increased resveratrol, physiological loss in weight, and decreased sensory values	Cayuela et al. (2009)
Guava	Gaseous ozone (8 ml s ⁻¹)	Ambient	Increase in total flavonoid was observed with 10 min exposure while prolonged exposures decreased phenolics and nutritional properties	Alothman et al. (2010)
Longan cv. Daw	Gaseous ozone (200 µl l ⁻¹)	25 °C	Decreased browning and oxalic acid content	Whangchai, Saengnil, and Uthaitutra (2006)
Mango cv. Palmer	Aqueous ozone	ambien	Greater TSS, titratable acidity, ascorbic acid content, flavonoids, carotenoids, and total antioxidant activity	Monaco et al. (2014)
Papaya cv. Sekaki	Gaseous ozone (2.5 µl l ⁻¹)	Ambient conditions	Maintained higher total soluble solids, vitamin C content, β-carotene, lycopene, total antioxidant activity, and visual quality	Ali, Ong, and Forney (2014)
Pineapple	Gaseous ozone (8 ml s ⁻¹)	Ambient conditions	Enhanced nutritional value with an increase in total flavonoids and phenolic compounds	Alothman et al. (2010)
Red bell peppers	Aqueous ozone (1 mg l ⁻¹)	Cold storage	Retained quality characteristics	Alexandre et al. (2011)
Strawberries	Aqueous ozone (8 and 10 mg l ⁻¹)	Ambient and 4 °C	No influence over advantageous biothiols (cysteine and γ-glutamylcysteinylglycine) levels and other quality parameters	Demirkol et al. (2008); Wei et al. (2007)
Strawberry	Gaseous ozone treatment (4 mg l ⁻¹)	Cold storage	Sustained vitamin C content, peroxidase (POD), catalase (CAT) activities, and reduced malondialdehyde (MDA) content	Zhang et al. (2011)
Strawberry	Gaseous ozone treatment (40 mg l ⁻¹)	Ambient	Sustained optimal levels of advantageous biothiols (cysteine and γ-glutamylcysteinylglycine)	Demirkol et al. (2008)
Tomato cv. Carousel	Gaseous ozone (1 µmol mol ⁻¹)	13 °C	Maintained glucose and fructose levels in the fruits with transient raise in β-carotene, lutein, and lycopene content	Tzortzakis, Singleton, and Barnes (2007)
Tomato cv. Elegance	Gaseous ozone (0.5 mg g ⁻¹)	15 °C	Improved glucose and fructose levels	Shailuf (2012)
Tomato cv. Thomas	Gaseous ozone (4 µl l ⁻¹)	5 °C	Sustained quality in terms of fructose, glucose, fumaric acid, and vitamin C content and prevented off-flavor development	Aguayo, Escalona, and Artes (2006)

systems. Also, ozone is not considered as a carcinogen or mutagen as it does not accumulate in fatty tissue or cause long-term chronic effects (Cohen et al. 2003). Thus, it is clear that ozone can be used safely. Nevertheless, measures must be taken to avoid needless exposure to ozone in the work area. Proper personnel protective equipment, exhausting systems, destruct units, and monitors should be used while operating with ozone in fresh produce storage units (Xu 1999).

Impact of ozone on the environment

Environmental and health organizations were expressing concerns about the byproducts formed with traditional sanitizing agents such as trihalomethanes in the wastewater generated in processing units and their return to the environment causing water pollution (Zhang et al. 2020). The buildup of such deadly chemicals in the water bodies has resulted in serious issues and attracted worldwide attention toward the safe use of disinfectants, sanitizers, bleaching agents, and other chemicals used in the food processing industry on a regular basis. The processing industries are greatly alarmed about the risk of impending regulatory restrictions with the traditional disinfectant chemical chlorine.

This growing concern about the release of chemical residues and other lethal byproducts with the use of traditional chlorine-based washing systems has created a huge concern regarding possible ground water and environmental pollution. Since the ozonation technology was proved to be free from residues and aids in degradation of pesticide/other chemical residues, it is being widely accepted as an eco-friendly alternative to the conventional chlorine-based disinfectants in the processing industries (Zhang et al. 2020).

Regulatory and legislative issues of ozone

Since 1906, ozone is being used commercially for sterilization of water initially and later extended to the food industry for preservation of the produce and sanitization of the produce-contact surfaces (Hill and Rice 1982). The legislations governing ozone application in the horticulture industry were developed in response to the growing usage of ozone as a multifunctional preservative and sanitizing agent. With the introduction of appropriate legislations on usage of ozone for food processing, there would be more regularization and encouragement of its use in the fruit and vegetable processing industries as an alternative for the conventional sanitizers (Tiwari and Rice 2012). Thus, the food processors are directed to

consult the governing bodies to determine whether the limitations, if any, exist in their proposed process of product development.

The US Food and Drug Administration (FDA) has permitted the usage of ozone for surface sanitization of fresh fruits and vegetables, disinfection of packing supplies, decontamination of process water, processing equipment, and food storage areas (Mahapatra, Muthukumarappan, and Julson 2005). In the United States, FDA has permitted the usage of ozone as an antimicrobial agent for fresh and fresh-cut fruits as well as vegetables. Ozone also has the status of GRAS (Generally Recognized as Safe) in USA for disinfection of bottled water and as a disinfectant for water bottling industries (FDA 1995). However, it was given GRAS status for use in direct contact with foods during 1997, by an independent expert panel set up by Electric Power Research Institute (EPRI) (Graham et al. 1997). In response to the petition filed by the EPRI during 2001, FDA has released an ultimate legislation modifying all other previous regulations related to food additives and granted permission for ozone to be used as an antimicrobial disinfectant in direct contact of food materials (FDA 2001; Hampson 2001).

Hence, a Global Harmonization Initiative (GHI) was initiated in 2004 by international division of US-based Institute of Food Technologists (IFT) in collaboration with the European Federation of Food Science and Technology (EFFoST). This network of scientific bodies and individual scientists work for promoting the harmony with world food safety rules and regulations. The GHI strives to ensure the easy availability of safe and delicious food to consumers all over the world (Tiwari and Rice 2012).

Conclusion


Although ozone treatment was known for more than a century, its recognition was driven lately by the environmentalists and researchers after investigating its high reactivity and impulsive disintegration into nontoxic byproducts. It was also found to be highly reactive and possess good penetration power. This ozone technology was found to have potential for replacing the conventional chemical-based sanitizers in fruit and vegetable processing industries. Suitable exploration of industrialized usage of gaseous and aqueous ozone has ensured greater disinfection competencies with minor injury to fresh produce and environmental safety. Being identified as an alternate sanitizer, ozone has replaced all the traditional sanitizing agents used for surface decontamination of the fresh horticulture produce and the processing equipment including recycling of the food-processed waste water. It


was also approved as a Generally Recognized As Safe (GRAS) sanitizer by FDA because of its eco-friendly nature (degradation into nonharmful oxygen after a short half-life) in addition to its inherent antimicrobial and antiethylene activity. All these benefits turn it very lucrative to the food industry, and conclusively, international food scientists are now endorsing the usage of ozone as a potential food processing agent. However, research should be emphasized toward standardization of optimum ozone concentration, mode of application (gaseous/aqueous), and time of exposure specific to the commodities.


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No potential conflict of interest was reported by the author(s).

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