IUFoST Strengthening Global Food Science and Technology for Humanity

IUFoST Scientific Information Bulletin (SIB)

October 2022

Fresh Produce Decontamination: Adapting to a World of Sustainable Resources

Abstract

Although decontamination is used widely in the food industry, it is generally more challenging and resource intensive when applied to fresh produce. Decontamination of fresh produce entails application of microbiocidal treatment (e.g., use of sanitizers), which is often accompanied or preceded with product washing. The most resource-intensive decontamination procedure is used with the “fresh-cut” produce category. In this case, water is applied liberally to wash the product with concomitant or subsequent sanitizer application. Although this process is intended to reduce fresh produce microbial load, it may increase product cross-contamination. If done right (e.g., monitoring and maintaining acceptable sanitizer level throughout the process), the operation can reduce product spoilage and alleviate illnesses resulting from pathogen transmission. Considering the ongoing climate change and the anticipated freshwater shortage, the industry needs to economize water usage; however, this should not be done at the expense of product safety. Similarly, processors should find alternatives to the traditionally used aqueous sanitizers, to cut down on pollution and on the costly disposal of processing water. The industry may consider waterless sanitization procedures with a preceding aqueous rinsing or a brief washing. Non-aqueous or gaseous decontamination technologies, such radiation, cold plasma, ozone, and chlorine dioxide, have been tested and seem promising. To make these alternative technologies industrially applicable, extensive optimization and scale-up efforts are needed with industry and government support.

Introduction

Driven by evidence that positively associates fresh produce intake to human health, one of the U.S national dietary objectives is to increase consumption of fruits and vegetables among people aged two years and over. The current phase of this initiative is known as “Healthy People 2030” (U.S. Department of Health and Human Services, 2020). A similar plan was initiated for European countries (WHO, 2014). Contrary to this positive outlook, microbially attributed foodborne illnesses due to consumption of these products are on the rise. According to the Center for Disease Control and Prevention data, fresh produce accounted for approximately 30% of all food-associated illnesses in the USA between 2009 and 2018 (CDC, 2022).

It is widely recognized that fresh produce is subject to microbial contamination throughout the supply chain, from the production sites in open fields or greenhouses to our kitchen counters. Production, washing, sanitizing, processing, transporting, warehousing, and retailing of fresh produce are resource-intensive operations and attempts to decrease the produce-associated disease risks are likely to further strain these resources. Meanwhile, awareness of the need for sustainable resources is also increasing, which calls for the industry to explore new approaches for fresh produce operations. Currently used fresh produce decontamination technologies and ways to improve the sustainability of these processes will be covered in this article.

Keeping Fresh Produce Fresh

Although “produce” has been broadly defined by some regulatory agencies (e.g., U.S. Code of Federal Regulations, 2022b) as the consumable raw agricultural commodities, which include fruits, vegetables, mushrooms, sprouts, peanuts, tree nuts, and herbs, the term “fresh produce” is more narrowly described in common literature. Fresh produce is perceived as perishable agricultural commodities that humans consume in the fresh state. Historic arguments about what is considered “fresh” did not lead to a conclusive definition, but in case of fresh produce this debate may be settled if the biological interpretation of freshness is considered. The plant parts that constitute fresh produce contain tissues made of live cells; when the viability of these cells is lost, biological processes that maintain the tissues’ intact structure and vital functions will cease and signs of deterioration or spoilage (i.e., loss of freshness) become apparent. Consequently, loss of freshness coincides with extended storage when live tissues enter a state of senesce as the product ages (Woo et al., 2018). Environmental factors, such as slow freezing and thawing, and unfavorable gaseous atmospheres affect the livelihood of produce tissues and thus cause loss of freshness. Processes that kill the live cells, such as fermentation, blanching, cooking, and retouring, alter the fresh state of produce considerably. Viability of these tissues not only determines product quality, it also contributes to its safety. Live plant cells may combat pathogenic microbial contamination owing to their innate defense mechanisms (George and Brandl, 2021). Therefore, viability of fresh produce tissues should be maintained to prevent loss of freshness, quality, and safety.

Fresh Produce Coverage

Assuming the “fresh” aspect has been clarified, the next issue is which agricultural commodities are included within the fresh produce category. Limiting this group to plant commodities would exclude mushrooms which are fungi and are considered fresh produce. Within fresh produce of plant origin, it is common to divide these products into fruits and vegetables. However, controversy arises when items like tomatoes and cucumbers are considered vegetables, although they develop from plant flowers, and thus are considered fruits from the botanical point of view. Additionally, nuts—which are dry commodities—are not considered fresh produce. To avoid these controversies, fresh produce simply may be considered as the raw agricultural commodities that have high-water activity and are consumed in a fresh state that is not much different from the state at which they were harvested. Plant parts that are edible when fresh include roots such as carrots, stems such as asparagus, leaves such as cilantro, flowers such as broccoli, and fruits such as tomatoes, apples, melons, and strawberries. Sprouted seeds, such as alfalfa and soybean sprouts, are eaten raw and considered fresh produce. Fresh produce also includes edible fungi fruiting bodies, which is limited to nonpoisonous mushrooms. A broader definition, covering what is included and excluded under the term “fresh produce”, is provided by regularity authorities such as the United States Food and Drug administration (U.S. Code of Federal Regulations. 2022b).

Diverse Products, Diverse Decontamination Approaches

The term fresh produce encompasses products that are incredibly diverse in physiological, structural, and physical characteristics. Physically, different products vary in size, surface, texture, porosity, and others. For example, surfaces range from thick and rough rind (e.g., cantaloupe) to rindless (e.g., strawberries), and texture ranges from hard (e.g., carrots) to soft (e.g., leavy greens). Most of the products are harvested in a metabolically active state, thus they should be cooled without delay to slow down senescence and ripening (Mahajan et al., 2014). Prompt cooling also delays microbial growth; hence, it increases product shelf life and improves its safety. Hydrocooling, vacuum cooling, or forced-air cooling is applied depending on the product. Preparing fresh produce before washing and sanitizing also varies with the product. These preparations include trimming inedible parts, removing damaged units, size sorting, and others. Additionally, some products are marketed intact whereas others are cut; the last category is known as “fresh-cut.” Compared to the fresh-cut, intact fresh produce often receives less processing in the packing facility. Other products (e.g., strawberries) receive minimal preparation or processing; washing such products could speed their spoilage.

Due to product diversity, a one-size fits-all decontamination strategy is not possible. Developing and implementing a successful decontamination strategy, regardless the targeted product, requires considerable planning (Krauter et al., 2011). In the case of fresh produce, decontamination is limited to the product surface. Volumetric decontamination is difficult to implement considering that the applied biocidal agent can be lethal to internal tissues and thus cause loss of product freshness. If done effectively, surface decontamination may be sufficient to decrease disease risk, if significant pathogen internalization did not occur. Surface decontamination of an object, whether it is a piece of equipment, a skin wound, or fresh produce, often starts with a washing step—it is difficult to decontaminate unclean surfaces. The goal of washing is to remove visible foreign materials, commonly is referred to as "soil." Soils, which are organic or inorganic particulate material, may act as a barrier between contaminating microorganisms and the applied biocidal agent. Additionally, soils may simply consume that agent, thus reducing its dose to levels insufficient to act on the targeted microorganisms. After washing, biocidal agents are applied; these could be chemicals (i.e., sanitizers) or physical agents (Table 1). Although hypochlorites are the most used sanitizers, processors have the option to use others such as peracetic acid, chlorine dioxide, or ozone. Despite product and procedural diversity, there are common features in fresh produce decontamination, which will be addressed in this article.

Washing and Sanitizing Fresh-Cut Produce

In addition to sorting, trimming, and cutting, fresh-cut processing typically includes three water-based steps; washing, sanitizing, and final rinsing. The distinction between washing and sanitizing is easier conceptually than practically, as these operations overlap in most facilities. For simplicity, a schematic representing these steps is shown in Fig. 1. The initial washing removes soils and surface contaminants. To prevent buildup of contaminants while this water is recycled, it is treated with sanitizer before being reused. In the next step, fresher water and sanitizer are used; the assumption is the sanitizer will act efficiently on microbial contaminants on the recently cleaned surfaces of treated produce. There is growing evidence that the sanitizer simply acts against the planktonic microorganisms removed from surfaces during water application, rather than on those residing on produce surfaces; this point will be discussed later. Adding organic surfactants would facilitate releasing bacteria lodged on surfaces into the circulating water (Sapers, 2014), but these surfactants would decrease the efficacy of sanitizers such as hypochlorites (Steinhauer, 1978), cause frothing of the sanitizing solution, and leave detergent residues on the final product. Fresh produce may receive a final water rinse to remove sanitizer residues; however, some processors choose to apply sanitizer in the final rinse as assurance that the product is protected in the package. Subsequently, the fresh-cut produce is subjected to spinning or centrifugation to remove free rinse water and then packaged. All waters used in washing, sanitizing, and rinsing are maintained cold and treated with sanitizers before reuse.

Numerous biocidal agents are used in fresh produce decontamination (Table 1). Most of these agents are used in the aqueous states, but others are applied in a non-aqueous state (e.g., gamma radiation) or as gases (chlorine dioxide and ozone). The mechanisms of interaction of the biocidal agents with organic matter not only give clues on how these agents are lethal to microbial contaminates (Table 1), but they also help us understand the potential economic burden resulting from the disposal of the associated processing water. Use of chlorine-based sanitization technologies not only results in hazardous reaction byproducts such as trihalomethanes and other organochlorines (U.S. Environmental Protection Agency, 2000), but it may also trigger an action by municipalities requiring a dechlorination step before discharge of processing water. For example, regulations by Arlington County, Virginia, USA, calls for dechlorination of discharged water if it contains >25 ppm free chlorine (Arlington County, 2022); such a level is easily attainable in fresh produce processing water. Similar to chlorine-based biocides, acids used in fresh produce decontamination require neutralization before the discharge of the associated processing water.

Oxidizing biocides are not known to generate toxic reaction byproducts; hence, they are less hazardous to health and more friendly to the environment than the other biocidal agents used in decontamination of fresh produce. High humidity increases efficacy of the non-aqueous and gaseous biocides; however, considering that fresh produce is ideally washed before any biocide is applied, moisture availability should not be a limiting factor.

Where do Sanitizer and Microbe Interact? Produce Surface vs. Recycled Water

During typical washing and sanitization of fresh produce (Figure 1), many researchers (e.g., Lou et al., 2018; Sapers, 2014) presumed the process to proceed as follows. Water application on the incoming produce loosens surface contaminants; therefore, attached cells turn into the planktonic state. These cells are carried in the flume water, which is separated from produce, and treated with the sanitizer. At this stage, sanitizer acts on the microbial contaminants in the flume water before it is reused on new incoming produce. In support of this scenario, researchers noticed that the sanitizers lose efficacy in the presence of fresh produce; hence, that antimicrobial action must happen before the flume water remixes with produce. As a corollary to this scenario, efficacy of applied biocide gradually decreases as organic load increased in flume water during its continuous reuse.

Consistent with this scenario, my research team (Kim et al., unpublished data) executed experiments on a pilot-scale equipment that was designed to simulate the washing or sanitization stage of an industrial fresh-cut processing line (Fig. 2). Whole iceberg lettuce was cut and pre-washed manually before feeding into the equipment at the rate of 5 lbs/min. For washing simulation, tap water containing inorganic wetting agent (0.1% tetra sodium pyrophosphate) was fed at the rate of 13.2 gal/min. Sanitization in this experiment was done using ozonated water (10 ppm), which also was fed at 13.2 gal/min. The setup included a dewatering step at the end of the line, using a vibratory draining conveyor. The continuous washing or sanitizing process lasted 20 min at least, and water or ozonated water was recycled during this operation. Cut lettuce was analyzed to determine populations of natural contaminants before the treatment and during the continuous washing or sanitization. Results (Fig. 3) show that washing alone slightly decreased microbial population during the first five min of operation, but the population gradually increased during the remainder of the treatment. On the contrary, application of the sanitizer for 10 min decreased the microbial populations on lettuce by approximately one log CFU/g, and the population tended to level off during the remainder of the continuous operation. Note that ozone was applied in the collection tank, and it was depleted quickly because of water's organic load. Therefore, water with small residual ozone was rescued to wash new incoming lettuce. These results imply that the sanitizing effect of aqueous ozone was due mainly to action of the biocide on microorganisms in the recycled water rather than on those remaining on the surface of fresh produce.

Within a fresh-cut produce operation, recycled processing water can contaminate incoming produce if such water was not decontaminated appropriately. Additionally, if a portion of incoming product is highly contaminated with pathogens (e.g., due wild animal incursion in the field), cross contamination of subsequently processed potions can occur. Controlling cross contamination in produce packing facility has been emphasized in recent publications (Gomnas et al., 2017; López-Gálvez et al., 2021). Luo et al. (2018) found that maintaining free chlorine in wash water at 10 ppm, or higher, minimizes cross contamination of fresh produce during processing.

Economizing Water Use

Water is often used abundantly to irrigate fresh produce in fields. Concerns have been raised about sustaining the amounts of water needed for this purpose. Taking Salinas valley is the US as an example of areas dedicated to growing fresh produce, the aquifer is an important source of the irrigation water in that valley. Depletion of this water source can lead to increased soil salinity; this prompted growers to use drip instead of flood irrigation, and to replenishing depleted aquifer using recycled wastewater (Smoley, 2021; Xia, 2015). Maintaining the microbiological quality of fresh produce irrigation water is indirectly related to water sustainability. Reliance on recycled wastewater, without a doubt, raises consumers safety risks. Many pathogenic contaminates on fresh produce can be attributed to irrigation water (Uyttendaele et al., 2015). Hence, measured to control pathogenic contaminants in fresh produce irrigation water have been proposed (Banach and van der Fels-Klerx, 2020), but great efforts are needed to make such measures applicable.

In addition to irrigation in the fields, various post-harvest operations require copious amounts of water. Use of water post-harvest may start before the produce leaves the field. In the case of lettuce, for example, water is applied on the freshly harvested produce as a rinse or a spray to keep the product's freshness and to compensate for moisture loss during the product's journey through the supply chain. Although the spry water may contain sanitizer, this application is likely of no value in terms of product decontamination. Water also is applied to other freshly harvested products but quantity and quality of harvest washing water vary.

Processes applied to fresh produce, such as cooling, peeling, rinsing, washing, fluming, and sanitizing, depend heavily on water use. Some products, such as leafy greens and celery, are "conditioned" daily at retail establishments by applying sanitizer-containing water in the form of a dip or a spray (Culbertson, 2014). Although conditioning is done mainly to maintain product turgor and to minimize welting, it may be of value in reducing microbial load. The most resource-intensive decontamination procedure is applied on fresh-cut produce. In this case, water is applied copiously to rinse and wash the product, transport it by fluming, and subsequently sanitize it. In a typical facility, flume and spray waters are collected, filtered, decontaminated, and reused (Fig. 1). Although this process is intended to reduce fresh produce microbial load, reuse of the water may increase product contamination if sanitizers are not applied adequately on the return stream (Luo et al., 2018).

Based on a study completed in Finland (Lehto et al., 2014) and covered four vegetable processing facilities, water consumption was 1.5 to 5.0 m^3 per ton of finished product, but other researchers reported much higher numbers (Manzocco et al., 2015). Considering anticipated climate change and the associated freshwater shortage, the industry needs to consider economizing water usage without increasing the risk of food-transmitted diseases. Additionally, processors should find alternatives to currently used sanitizers, to cut down on pollution and the costly disposal of processing water. Some processors aim at "zero water discharge" in fresh produce packing facilities, but this goal is economically and technologically challenging. The most used sanitizer in the food industry is hypochlorite, which is applied in water. Instead, the industry should consider implementing waterless sanitization procedures, along with a preceding aqueous rinsing or brief washing.

Gaseous and other non-aqueous decontamination procedures have been tested and produced promising results (Table 1). Ozone (Fan, 2021) and chlorine dioxide (Malka and Park, 2022; Singh et al., 2021) are promising antimicrobial gases for decontamination of fresh produce. These have the advantage of reaching to a depth in fresh produce tissues that cannot be attained by aqueous sanitizers (Shynkaryk et al., 2015). When used in fresh produce decontamination, the antimicrobial gases are produced in proximity to the product to be treated (i.e., on-site), should be properly handled, and contained to protect worker, and their levels are carefully monitored and controlled. Using ozone gas as a sanitizer during fresh produce vacuum cooling or transportation to distant locations was suggested based on experimental findings (Vurma et al., 2007). Currently, this antimicrobial gas is used by some companies on fresh produce transport trucks (A.E. Yousef, personal communication) and in temporary storage facilities (Suslow, 2018). In addition to the antimicrobial effect, treatment of fresh produce in storage facilities with ozone degrades the biologically-release ethylene and thus delays product senesce during storage (Skog and Chu, 2001). Similarly, gaseous chlorine dioxide can be used effectively in fresh produce decontamination (Han et al, 2000; Malka and Park, 2022). Antimicrobial gases and other non-aqueous biocides not only decrease water dependance in fresh produce decontamination but may also act on microorganisms residing on product surfaces or in crevices. These biocides can even replace chlorine in decontaminating recycled water without leaving undesirable or harmful reaction products. Other non-aqueous decontamination technologies such as cold plasma should be considered industrially. Ionizing radiation is not a novel decontamination technology, but this approach may be revisited experimentally and industrially. Although antimicrobial gases and other non-aqueous sanitization technologies seem feasible for fresh produce decontamination, these have not been optimized for industrial applications. Extensive optimization efforts are needed with industry and government support.

References

Alexandre EMC, Brandão TRS, Silva CLM. 2012. Assessment of the impact of hydrogen peroxide solutions on microbial loads and quality factors of red bell peppers, strawberries and watercress. Food Cont 27:362–368. https://doi.org/10.1016/j.foodcont.2012.04.012

Arlington County, 2022. Discharging chlorinated water. Department of Environmental Services, Arlington County, USA. https://www.arlingtonva.us/Government/Programs/Water-Utilities/Discharging-Chlorinated-Water (Accessed October 3, 2022)

Artés F, Gómez P, Aguayo E, Escalona V, Artés-Hernández F. 2009. Sustainable sanitation techniques for keeping quality and safety of fresh-cut plant commodities. Postharvest Biol Technol 51:287–296. https://doi.org/10.1016/j.postharvbio.2008.10.003

Banach JL, van der Fels-Klerx HJ. 2020. Microbiological reduction strategies of irrigation water for fresh produce. J Food Prot 83:1072–1087

Beuchat LR, Nail BV, Adler BB, Clavero MRS. 1998. Efficacy of spray application of chlorinated water in killing pathogenic bacteria on raw apples, tomatoes, and lettuce. J Food Prot. 61:1305–1311.

Blanco Y, de Diego-Castilla G, Viudez-Moreiras D, Cavalcante-Silva E, Rodriguez-Manfredi JA, Davila AF, McKay CP, Parro V. 2018. Effects of gamma and electron radiation on the structural integrity of organic molecules and macromolecular biomarkers measured by microarray immunoassays and their astrobiological implications. Astrobiology 18:1497–1516. https://doi.org/10.1089/ast.2016.1645

Center for Disease Control and Prevention. 2022. CDC and food safety. https://www.cdc.gov/foodsafety/pdfs/cdc-and-food-safety.pdf (accessed October 3, 2022)

Chawla AS, Kasler DR, Sastry SK, Yousef AE. 2012. Food decontamination using ozone, p 495–532. *In* Demirci A, Ngadi M (ed), Microbial decontamination in the food industry: novel methods and applications. Woodhead Publishing, Cambridge, UK.

Culbertson GS. 2014. Investigating methods of conditioning fresh vegetables in retail establishments and exploring procedural modifications that improve product quality and safety. Masters Theis, The Ohio State University, Columbus, Ohio, USA. http://rave.ohiolink.edu/etdc/view?acc_num=osu1397488227

Curci R, Edwards JO. 1992. Activation of hydrogen peroxide by organic compounds, pp 45–95. *In* Strukul G (ed), Catalytic oxidations with hydrogen peroxide as oxidant. Springer, New York, USA.

Fan X. 2021. Gaseous ozone to preserve quality and enhance microbial safety of fresh produce: Recent developments and research needs. Compr Rev Food Sci Food Saf 20:4993–5014. https://doi.org/10.1111/1541–4337.12796

Ganiev IM, Timergazin QK, Kabalnova NN, Shereshovets VV, Tolstikov GA. 2005. Reactions of chlorine dioxide with organic compounds. Eurasian ChemTech J 7:1–31.

George AS, Brandl MT. 2021. Plant bioactive compounds as an intrinsic and sustainable tool to enhance the microbial safety of crops. Microorganisms 9, 2485. https://doi.org/10.3390/microorganisms9122485

Gombas D, Luo Y, Brennan J, Shergill G, Petran R, Hau H, Walsh R, Khurana K, Zomorodi B, Rosen J, Varley R, Deng K. 2017. Guidelines to validate control of cross-contamination during washing of fresh-cut leafy vegetables. J Food Prot 80:312–330.

Graça A, Santo D, Pires-Cabral P, Quintas C. 2020. The effect of UV-C and electrolyzed water on yeasts on fresh-cut apple at 4°C. J Food Eng 282:110034. https://doi.org/10.1016/j.jfoodeng.2020.110034

Han Y, Sherman DM, Linton RH, Nielsen SS, Nelson PE. 2000. The effects of washing and chlorine dioxide gas on survival and attachment of *Escherichia coli* O157: H7 to green pepper surfaces. Food Microbiol 17:521–533.

Hupperich K, Mutke XAM, Abdighahroudi MS, Jütte M, Schmidt TC, Lutze HV. 2020. Reaction of chlorine dioxide with organic matter – formation of inorganic products. Environ Sci Water Res Technol 6:2597–2606. https://doi.org/10.1039/d0ew00408a

Kemp MG, Sancar A. 2012. DNA excision repair: Where do all the dimers go? Cell Cycle 11:2997–3002. http://doi.org/10.4161/cc.21126

Kim J, Huang C-H. 2021. Reactivity of peracetic acid with organic compounds: a critical review. ACS ES&T Water 1:15–33. https://doi.org/10.1021/acsestwater.0c00029

Kim Y-J, Lee S-H, Park J, Park J, Chung M, Kwon K, Chung K, Won M, Song KB. 2008. Inactivation of *Escherichia coli* O157:H7, *Salmonella typhimurium*, and *Listeria monocytogenes* on stored iceberg lettuce by aqueous chlorine dioxide treatment. J Food Sci 73:M418–M422.

Kovačević VV, Dojčinović BP, Jović M, Roglić GM. Obradović BM, Kuraica MM. 2017. Measurement of reactive species generated by dielectric barrier discharge in direct contact with water in different atmospheres. J Phys D: Appl Phys 50:155205.

Krauter P, Edwards D, Yang L, Tucker M. 2011. A Systematic methodology for selecting decontamination strategies following a biocontamination event. Biosecurity and Bioterrorism: Biodefense Strategy, Practice, and Science 9:262–270. https://doi.org/10.1089/bsp.2010.0071

Lehto M, Sipilä I, Alakukku L, Kymäläinen H-R. 2014. Water consumption and wastewaters in fresh-cut vegetable production. Agric Food Sci 23:246–256.

López-Gálvez F, Allende A, Gil MI. 2021. Recent progress on the management of the industrial washing of fresh produce with a focus on microbiological risks. Curr Opin Food Sci, 38:46–51

Luo Y, Zhou B, Van Haute S, Nou X, Zhang B, Teng Z, Turner ER, Wang Q, Millner PD. 2018. Association between bacterial survival and free chlorine concentration during commercial fresh-cut produce wash operation. Food Microbiol 70:120–128.

Mahajan PV, Caleb OJ, Singh Z, Watkins CB, Geyer M. 2014. Postharvest treatments of fresh produce. Phil Trans R Soc A. 372: 20130309. http://doi.org/10.1098/rsta.2013.0309

Malka SK, Park M-H. 2022. Fresh produce safety and quality: chlorine dioxide's role. Front Plant Sci 12:775629. http://doi.org/10.3389/fpls.2021.775629

Manzocco L, Ignat A, Anese M, Bot F, Calligaris S, Valoppi F, Nicoli MC. 2015. Efficient management of the water resource in the fresh-cut industry: Current status and perspectives. Trends Food Sci Technol 46:286–294. http://doi.org/10.1016/j.tifs.2015.09.003

Munger K. 2015. Method for disinfecting, sanitizing, and packaging ready-to-eat produce. US Patent 9,095,152 B2.

Niemira BA. 2012. Cold plasma decontamination of foods. Annu Rev Food Sci Technol 3:125–142. http://doi.org/10.1146/annurev-food-022811-101132

Sapers GM. 2014. Disinfection of contaminated produce with conventional washing and sanitizing technology, pp 389–431, *In* Matthews KR, Sapers GM, Gerba CP (ed). The produce contamination problem, causes and solutions, 2nd ed. Elsevier Inc., Amsterdam, Netherlands.

Shiroodi SG., Ovissipour M. 2018. Electrolyzed water application in fresh produce sanitation, pp 67–89. *In* Siddiqui MW (ed), Postharvest disinfection of fruits and vegetables. Elsevier Inc., Amsterdam, Netherlands. https://doi.org/10.1016/B978-0-12-812698-1.00003-0

Shynkaryk MV, Pyatkovskyy T, Mohamed HM, Yousef AE, Sastry SK. 2015. Physics of fresh produce safety: role of diffusion and tissue reaction in sanitization of leafy green vegetables with liquid and gaseous ozone-based sanitizers. J Food Prot 78:2108–2116. http://doi.org/10.4315/0362-028X.JFP-15-290

Silvetti T, Pedroni M, Brasca M, Vassallo E, Cocetta G, Ferrante A, De Noni I, Piazza L, Morandi S. 2021. Assessment of possible application of an atmospheric pressure plasma jet for shelf life extension of fresh-cut salad. Foods 10:513. https://doi.org/10.3390/foods10030513

Singh S, Maji PK, Lee SS, Gaikwad KK. 2021. Applications of gaseous chlorine dioxide for antimicrobial food packaging: a review. Environ Chem Ltr 19:253–270. https://doi.org/10.1007/s10311-020-01085-8

Skog LJ, Chu CL. 2001. Effect of ozone on qualities of fruits and vegetables in cold storage. Can J Plant Sci 81:773–779.

Smoley R. 2021. Salinas Valley protects itself from drought. Blue Book Services, Carol Stream, IL, USA. https://www.producebluebook.com/2021/11/12/Salinas-valley-protects-itself-from-drought/# (accessed October 3, 2022)

Steinhauer AF. 1978. Stable cleaning agents of hypochlorite bleach and detergent. US Patent 4,071,463.

Suslow, T. 2018. Food safety: Once more into the ozone. https://www.growingproduce.com/fruits/food-safety-ozone/ (Accessed October 3, 2022)

U.S. Code of Federal Regulations. 2022a. Ionizing radiation for the treatment of food. 21CFR179.26. https://www.accessdata.fda.gov/scripts/cdrh/cfdocs/cfcfr/cfrsearch.cfm?fr=179.26 (accessed October 3, 2022)

U.S. Code of Federal Regulations. 2022b. Standards for the growing, harvesting, packing, and holding of produce for human consumption. 21CFR112.1. https://www.accessdata.fda.gov/scripts/cdrh/cfdocs/cfcfr/cfrsearch.cfm?fr=112.1 (accessed October 3, 2022)

U.S. Department of Health and Human Services. 2020. Healthy people 2030; Nutrition and healthy eating. https://health.gov/healthypeople/objectives-and-data/browse-objectives/nutrition-and-healthy-eating (accessed October 3, 2022)

U.S. Environmental Protection Agency. 2000. Wastewater, technology fact sheet, dechlorination. EPA 832-F-00-022. https://www3.epa.gov/npdes/pubs/dechlorination.pdf (accessed October 3, 2022)

Uyttendaele M, Jaykus L-A, Amoah P, Chiodini A, Cunliffe D, Jacxsens L, Holvoet K, Korsten L, Lau M, McClure P, Medema G, Sampers I, Rao Jasti P. 2015. Microbial hazards in irrigation water: standards, norms, and testing to manage use of water in fresh produce primary production. Compr Rev Food Sci Food Saf 14:336–356. https://doi.org/10.1111/1541-4337.12133

Vandekinderen I, Devlieghere F, De Meulenaer B, Ragaert P, Van Camp J. 2009. Optimization and evaluation of a decontamination step with peroxyacetic acid for fresh-cut produce. Food Microbiol 26:882–888. http://doi.org/10.1016/j.fm.2009.06.004

Vurma M, Pandit RB, Sastry SK, Yousef AE. 2009. Inactivation of *Escherichia coli* O157:H7 and natural microbiota on spinach leaves using gaseous ozone during vacuum cooling and simulated transportation. J Food Prot 72:1538–1546. http://doi.org/10.4315/0362-028x-72.7.1538

Westerhoff P, Aiken G, Amy G, Debroux J. 1999. Relationships between the structure of natural organic matter and its reactivity towards molecular ozone and hydroxyl radicals. Water Res 33:2265–2276.

Woo HR, Masclaux-Daubresse C, Lim PO. 2018. Plant senescence: how plants know when and how to die. J Experiment Botany, 69:715–718. https://doi.org/10.1093/jxb/ery011

World Health Organization. 2014. European food and nutrition action plan 2015–2020. https://apps.who.int/iris/bitstream/handle/10665/329405/9789289051231-eng.pdf?sequence=1&isAllowed=y

Xia R. 2015. Salinas Valley's thriving crops mask fears over the area's lone water source. Los Angeles Times, El Segundo, CA, USA. September 7, 2015. https://www.latimes.com/local/california/la-me-drought-salinas-valley-20150907-story.html (accessed October 3, 2022)

Yang X, Shang C. 2004. Chlorination byproduct formation in the presence of humic acid, model nitrogenous organic compounds, ammonia, and bromide. Environ Sci Technol 38:4995–5001.

(Tables appended)

Fresh Produce Decontamination: Adapting to a World of Sustainable Resources was prepared by IAFoST Fellow, ***Professor Ahmed Youssef*****, Department of Food Science & Technology, Department of Microbiology, The Ohio State University, Columbus, OH 43210, US***A, on behalf of, and approved by, the IUFoST Scientific Council. This and the other titles in the series of IUFoST Scientific Information Bulletins are available online at http://iufost.org/iufost-scientific-information-bulletins-sib.*

IUFoST SCIENTIFIC COUNCIL 2020-2022: Dr. Fereidoon Shahidi (Chair), Dr. Hongda Chen (Chair-elect), Dr. V. Prakash (Past Chair), Dr. Stephane Guilbert (Councillor). General Secretariat, IUFoST,: secretariat@iufost.org, www.iufost.org

Table 1. Biocides, alphabetically ordered, that are used experimentally or commercially in decontamination of fresh produce and their reactivity with organic matter, which is indicative of their antimicrobial mechanisms.

Antimicrobial agents (active form)	**Reaction with organic matter**	**Dosage unit**	**Usage state**	**Usage example[a]**
Chemical biocides				
Chlorine/Hypochlorite (HOCl)	Chlorination/oxidation (Yang and Chang, 2004)	ppm, free chlorine	Aqueous	Apples, tomatoes, and lettuce (Beuchat et al., 1998)
Chlorine dioxide (ClO_2)	Oxidation/chlorination (Ganiev et al., 2005; Hupperich et al., 2020)	ppm, ClO_2	Gaseous or aqueous	Iceberg lettuce (Kim, et al., 2008)
Detergent-sanitizer combination (e.g., sodium lauryl sulfate + antimicrobial agent)	Detergent release surface-attached microbes before inactivated by the antimicrobial agent	Percent	Aqueous	Blueberries (Munger & Bros, 2015)
Electrolyzed water, acidic (HOCl)	Chlorination/oxidation (Yang and Chang, 2004)	ppm free chlorine or ORP[b] (Shiroodi and Ovissipour, 2018)	Aqueous	Fresh-cut apple (Graça et al., 2020)
Hydrogen peroxide (H_2O_2)	Oxidation (Curci et al., 1992)	Percent, H_2O_2	Aqueous	Peppers, strawberries, and watercress (Alexandre et al., 2012)
Ozone (O_3)	Oxidation (Westerhoff et al., 1999)	ppm (solution) or g ozone gas/g gas mixture (Chawla et al., 2012)	Gaseous or aqueous	Spinach (Vurma et al., 2009)
Peracetic acid (CH_3-CO_3H)	Oxidation (Kim and Huang, 2021)	ppm, CH_3-CO_3H	Aqueous	Fresh-cut carrots, cabbage, and iceberg lettuce (Vandekinderen et al., 2009)
Physical biocides				
Cold plasma	Oxidation and other mechanisms	Energy delivered	Non-aqueous	Lettuce leaves

($^{\bullet}$OH, O$^{\bullet}$, H_2O_2, O_3, UV, and other reactive species)	(Kovačević et al, 2017; Niemira, 2012)	(i.e., mA & kV)		(Silvetti et al., 2021)
Gamma radiation (Wavelength $<10^{-11}$ m; i.e., <10 pm)	Nucleic acid cross-linking and strand breaks (Blanco et al., 2018)	k Gray	Non-aqueous	Iceberg lettuce and spinach at ≤ 4.0 kGy. (U.S. Code of Federal Regulations, 2022a)
Ultraviolet radiation (UV-C:190-280 nm)	Nucleic acid base dimerization; pyrimidine dimers (Kemp and Sancar, 2012)	kJ/m^2 (Artés et al., 2009)	Non-aqueous	Fresh-cut apple (Graça et al., 2020)

[a] Each selected study reported at least one log reduction of generic population or a microorganism of concern on the treated fresh produce; treatment details are provided in the cited publication.

[b] Oxidation reduction potential.

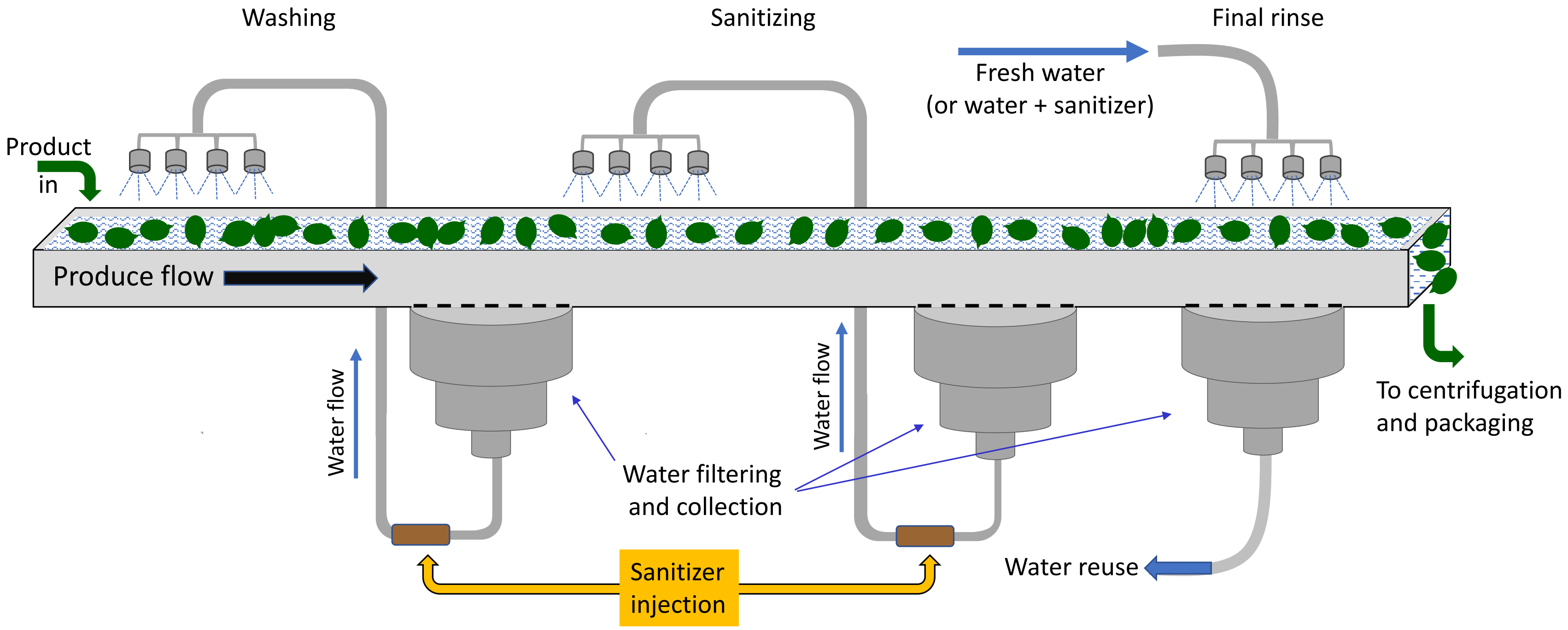

Fig. 1. Fresh produce decontamination; a conceptional schematic of fresh produce flume for product washing and sanitization.

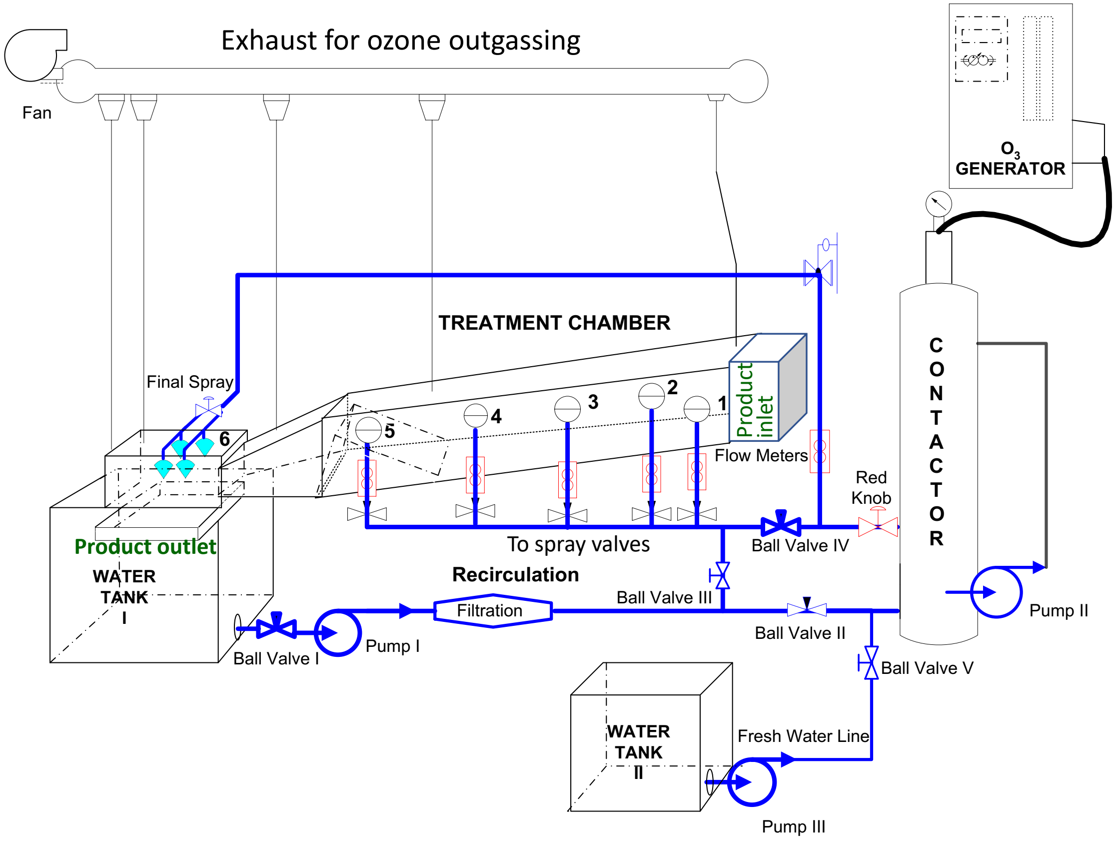

Fig. 2. Schematic of a pilot-scale equipment, simulating continuous industrial flume washer, used experimentally to test the efficacy of washing with or without aqueous ozone in decreasing cut lettuce microbial load.

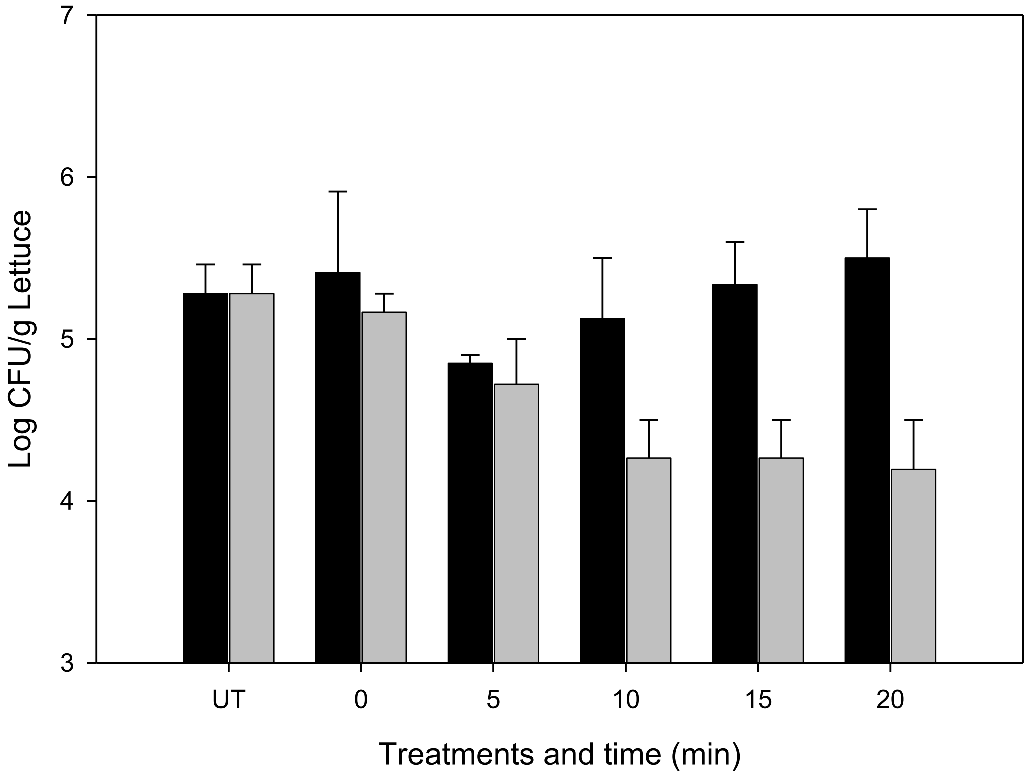

Fig. 3. Counts of natural mesophilic aerobic population of pre-washed cut lettuce when subjected to continuous washing or sanitization. Solid bars represent water washing; gray bars represent sanitization with water containing 10 ppm ozone; UT is untreated samples; time zero represents the counts in the pre-washed samples before being subjected to continuous washing or sanitization.