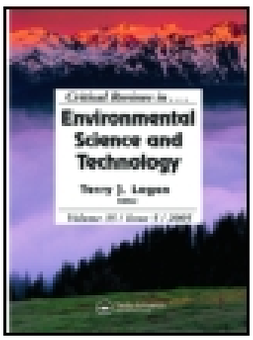

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Chlorine and ozone disinfection and disinfection byproducts in postharvest food processing facilities: A review

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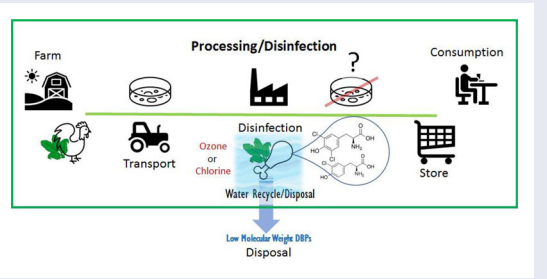
ABSTRACT



The application of chemical disinfectants in postharvest food processing facilities is important for the control of foodborne pathogen outbreaks. Similar to drinking water disinfection, food processors will need to optimize disinfectant exposures to balance pathogen inactivation against exposure to potentially toxic disinfection byproducts (DBPs). Since most disinfection research has focused on drinking water, this review summarizes research related to disinfection in food washing facilities, particularly by chlorination and ozonation. Although these disinfectants are also used for drinking water, the conditions are significantly different at food processing facilities. After a brief summary of foodborne pathogen outbreaks, this review describes food processing treatment trains, particularly the critical differences in conditions encountered relative to drinking water disinfection (e.g., short disinfectant contact times and high and variable disinfectant demands). The review discusses research related to pathogen inactivation and DBP formation by chlorine and ozone during washing of produce, meat and seafood. In particular, the research highlights the difficulty of inactivating pathogens on food, but the efficacy of these disinfectants for controlling pathogen cross-contamination through the washwater. While most research on food-associated DBPs has focused on the same, low molecular weight DBPs of interest in drinking water, these DBPs partition to the washwater. This review highlights the need for research on the initial transformation products of disinfectant reactions with biomolecules, since these products may present a risk for consumer exposure by remaining within the food.

KEYWORDS Chlorine; disinfection byproducts; ozone; pathogen inactivation; postharvest sanitization

1. Introduction

At the start of the twentieth century, the prevalence of waterborne diseases declined significantly after the application of chlorine to disinfect drinking water. However, researchers in the 1970s discovered that chlorine reactions

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with dissolved organic matter (DOM) produced potentially carcinogenic chlorinated disinfection byproducts (DBPs), such as trihalomethanes (THMs) (Li & Mitch, 2018; Rook, 1974). Thereafter, drinking water utilities sought to moderate disinfectant exposures to balance the acute risks associated with waterborne pathogens against the chronic risks associated with exposure to DBPs (Li & Mitch, 2018).

Foodborne pathogenic outbreaks are an increasing concern globally. The application of disinfectants in postharvest food processing facilities is an important method to control consumer exposure to foodborne pathogens. In the United States, the passage of the Food Safety Modernization Act may lead to the development of guidelines for disinfectant exposures to control foodborne pathogens (USFDA, 2011). Like drinking water treatment, these exposures ultimately must be optimized to balance the risks posed by pathogens and food-derived DBPs. While most research on DBPs has focused on drinking water, the conditions associated with disinfectant applications in postharvest food processing facilities are very different.

This review focuses on the application of chemical disinfectants, particularly chlorine and ozone, in postharvest processing facilities to prevent foodborne pathogenic outbreaks. Previous reviews have discussed foodborne pathogenic outbreaks, with a focus on the identification of pathways leading to contamination, including within postharvest treatment trains (Alegbeleye et al., 2018; Bennett et al., 2018; Kase et al., 2017; Makinde et al., 2020; Seymour & Appleton, 2001; Soon et al., 2020; WHO, 2015). Other reviews have discussed physical (e.g., heat, UV light) and chemical (e.g., hydrogen peroxide) alternatives to chlorine disinfection (Ali et al., 2018; Brodowska et al., 2018; De Corato, 2020; Deng et al., 2020; Esua et al., 2020; Meireles et al., 2016; Sohaib et al., 2016). These reviews focused on practical considerations for their implementation in postharvest settings and summarized their efficacy with respect to microbial inactivation, but featured little discussion of DBPs. After a brief summary of important aspects of foodborne pathogenic outbreaks, this review discusses the conditions and current practice for chlorine and ozone application in postharvest processing facilities. This review focuses on the central tradeoff between the efficacy of these disinfectants with respect to microbial control and the production of food-associated DBPs formation, and discusses directions for future research in this area.

2. Foodborne pathogen outbreaks

The World Health Organization (WHO) estimated that 31 foodborne pathogens caused 600 (95% uncertainty interval (UI), 420–960) million illnesses and 420,000 (95% UI, 310,000–600,000) deaths in 2010 (WHO,

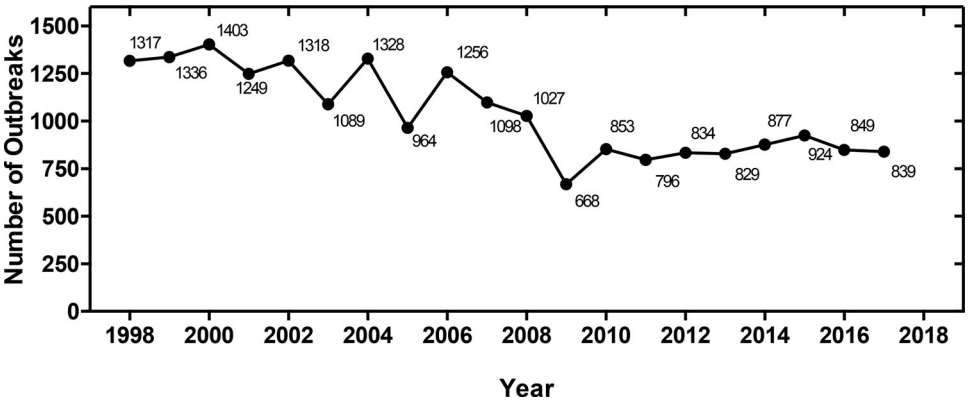

Figure 1. Number of foodborne pathogen outbreaks for the years 1998–2017 in the United States as reported on the National Outbreak Reporting System (NORS) provided by the United States Centers for Disease Control and Prevention (CDC, 2018b).

2015). Based on data from 2000 to 2008, the U.S. Centers for Disease Control and Prevention (CDC) estimated that 31 foodborne pathogens cause 9.4 (90% Credible Interval (CI), 6.6–12.7) million illnesses, resulting in 56,000 (90% CI, 39,500–76,000) hospitalizations and 1300 (90% CI, 710–2270) deaths annually in the United States (CDC, 2018a; Scallan et al., 2011). These values are likely to be underestimates, because many foodborne pathogen-associated illnesses may not be diagnosed as such by healthcare providers (Scallan et al., 2011). Figure 1 indicates that the number of annual foodborne outbreaks in the United States has declined over the past 20 years. Together, the CDC data suggest that a typical outbreak results in approximately 8000 illnesses. Foodborne illnesses are estimated to cost $55–93 billion annually in the United States, considering treatment costs and lost productivity (Scharff, 2015). In 2011, a Consumer Brands Association survey estimated that 77% of brands experienced losses of up to $30 million due to product recalls (GMA, 2011).

Table 1 provides the five foodborne pathogens estimated by the CDC to be responsible for the most illnesses, hospitalizations, and deaths in the United States between 2000 and 2008 (CDC, 2018a). Important foodborne pathogens include one virus (*Norovirus)*, one protozoan (*Toxoplasma gondii*) and several bacteria (non-typhoidal *Salmonella* spp., *Campylobacter* spp., *Listeria monocytogenes*, *Escherichia coli* O157:H7, and *Clostridium perfringens*) (CDC, 2018a; Kase et al., 2017). Outbreaks highlighted by the CDC between 2018 and 2020 were most frequently attributed to *Salmonella* spp. and *Escherichia coli* O157:H7 (CDC, 2020). Examples include a 2018 outbreak involving *Escherichia coli* O157:H7 on romaine lettuce with 210 reported cases, 96 hospitalizations and 5 deaths across 46 states (CDC, 2020), and a 2018 outbreak involving *Salmonella* Newport on ground beef

Table 1. Top five pathogens contributing to foodborne illnesses, hospitalizations, and deaths in the United States based on annual estimates from the years 2000–2008 (CDC, 2018a).

Pathogen	Illnesses	90% Credible interval	Percent (%)
Norovirus	5,460,000	3,230,000–8,310,000	58
Salmonella (non-typhoidal)	1,030,000	645,000–1,680,000	11
Clostridium perfringens	966,000	192,000–2,480,000	10
Campylobacter spp.	845,000	337,000–1,610,000	9
Staphylococcus aureus	241,000	72,300–529,000	3
Subtotal			91
Pathogen	Hospitalizations	90% Credible Interval	Percent (%)
Salmonella (non-typhoidal)	19,300	8540–37,500	35
Norovirus	14,700	8100–23,300	26
Campylobacter spp.	8460	4300–15,200	15
Toxoplasma gondii	4430	2630–6670	8
Escherichia coli (STEC) O157	2140	549–4610	4
Subtotal			88
Pathogen	Deaths	90% Credible Interval	Percent (%)
Salmonella (non-typhoidal)	378	0–1010	28
Toxoplasma gondii	327	200–482	24
Listeria monocytogenes	255	0–733	19
Norovirus	149	84–237	11
Campylobacter spp.	76	0–332	6
Subtotal			88

with 403 reported cases, 117 hospitalizations, but no deaths across 40 states (CDC, 2020). Outbreaks involving *Listeria monocytogenes* tend to have fewer reported cases, but higher percentages of cases resulting in hospitalization and death. For example, a *Listeria monocytogenes* outbreak in 2019 resulted in 24 cases, 22 hospitalizations and 2 deaths across 13 states (CDC, 2020), while a 2020 outbreak associated with enoki mushrooms involved 36 cases, 30 hospitalizations and 4 deaths across 17 states (CDC, 2020). On an international basis, Soon et al. (2020) found that *Salmonella* spp., *Escherichia coli*, and *Listeria monocytogenes* together accounted for 89% of cases (Figure 2). While there is an abundance of literature linking bacterial pathogens to foodborne illness outbreaks, other pathogenic groups, such as viruses and protozoans, have been understudied (Alegbeleye et al., 2018).

Pathogen contamination can occur preharvest via irrigation water. *Salmonella* spp. and *Escherichia coli* occur in the intestines of livestock, resulting in contamination of irrigation water directly by animal manure or via cross-contamination by flies and other insect vectors (Alegbeleye et al., 2018; Erickson et al., 2019; Jacobsen & Bech, 2012; Matthews et al., 2014; Verhaelen et al., 2013; Wasala et al., 2013). Whether pathogen contamination occurred preharvest and was not removed during processing, or was introduced during processing is often difficult to establish (Soon et al., 2020). Alegbeleye et al. (2018) reviewed potential pathways for pathogen contamination preharvest and postharvest. While raw produce and minimally processed foods are particularly at risk for pathogen contamination (CDC, 2020), many outbreaks highlighted by the CDC (2020) involve foods

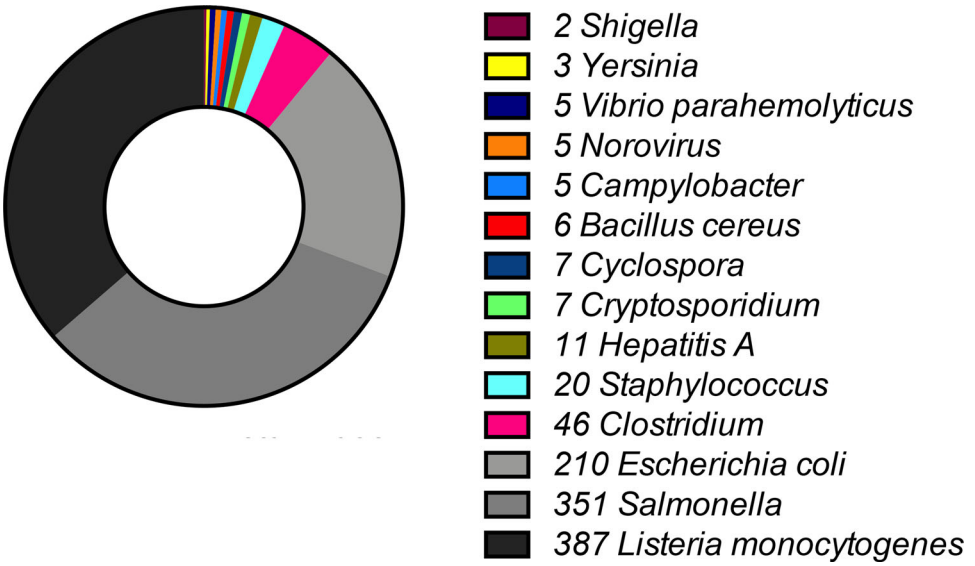

Figure 2. Number of foodborne pathogen outbreaks (1065 total) attributed to specific pathogens from 2008 to 2018 as compiled from data sets reported in Soon et al. (2020). Excluded are 111 outbreaks which were not attributed to specific pathogens.

that had undergone significant postharvest processing (e.g., cooking, shelling, and chopping), providing ample opportunity for cross-contamination by processing equipment (Kase et al., 2017; Nerín et al., 2016). For example, 11 of 41 outbreaks reported by the CDC between 2018 and 2020 involved precooked foods (CDC, 2020). Bennett et al. (2018) showed that 37% of 972 outbreaks that occurred in the United States were associated with processed foods, including salads (226 outbreaks), Mexican-style dips or salsas (62 outbreaks), and mixed vegetables (57 outbreaks).

Regarding whether outbreaks by specific pathogens tend to be more frequent on specific types of food, *Campylobacter* spp (Batz et al., 2012; CDC, 2020; Domingues et al., 2012; Ravel et al., 2017; Rossler et al., 2020) and *Escherichia coli* (Soon et al., 2020) illnesses are often attributed to raw meats. In addition to contamination of fruits and vegetables, *Salmonella* spp. can survive under dry conditions, such that contamination of nuts, chocolate, spices, and other dry products is a concern (Gross et al., 2016; Keller et al., 2013; Sheth et al., 2011; Soon et al., 2020; Uesugi et al., 2006; Werber et al., 2005). *Listeria monocytogenes* can withstand low pH, frigid temperatures, high salinity, and other hostile conditions (Gandhi & Chikindas, 2007) enabling it to persist even in heavily processed foods, including cooked meats and seafood, dairy products, and lunch meats (Boatemaa et al., 2019; CDC, 2020; EFSA, 2015; Gandhi & Chikindas, 2007; Soon et al., 2020; USFDA, 2019).

The importance of controlling pathogens during food processing is growing in concert with the growth in the consumption of minimally processed

fruits and vegetables (Wang et al., 2014) and ready-to-eat foods. Amid rising concerns over foodborne pathogen outbreaks in the United States, the Food Safety Modernization Act (FSMA) was passed in 2011 (USFDA, 2011). The FSMA will develop guidelines for irrigation water handling and other practices to minimize the introduction of pathogens, both preharvest and postharvest. However, given the hardiness of foodborne pathogens, such as *Listeria monocytogenes*, and the opportunities for cross-contamination within processing facilities, source control measures alone are inadequate. To control pathogens in drinking water, drinking water providers developed multiple treatment barriers (e.g., source water protection, filtration, and chlorine disinfection) to prevent consumer exposure to pathogens (Marron et al., 2019). A similar multiple barrier approach is needed for controlling foodborne pathogen outbreaks. In particular, disinfectants applied within postharvest food processing facilities serve as a key barrier to prevent consumer exposure to pathogens. This review focuses on chemical disinfectants, particularly chlorine and ozone, after briefly describing postharvest food processing treatment trains.

3. Overview of postharvest food processing facilities

Prior to transport to processing facilities, produce can be cut, trimmed, washed, and cooled to remove field heat, dust, and other extraneous materials by drenching with cooled water for approximately 10 min (i.e., hydrocooling) or by vacuum cooling (Gil et al., 2015; Grandison, 2011; Shynkaryk et al., 2016). Chemical sanitizers may be applied during these field washes. After inspection to remove damaged produce, produce can be shredded, sliced, or peeled in the postharvest facility (Figure 3). Produce is then washed with water to remove soil and other extraneous materials (Gil et al., 2015; Grandison, 2011). Washwaters can be applied via immersion tanks or by sprayers. Particularly for ready-to-eat produce (e.g., packaged spinach or mixed salads, table grapes, broccoli florets, peeled and cored pineapples, and fresh sauces), triple-washing may be practiced, consisting of rinses in the field and immersion in two separate tanks at postharvest washing facilities (FSAI, 2001; Grandison, 2011; Gross et al., 2016).

As noted previously, produce can be contaminated with pathogens via irrigation water (Brandl, 2006; Doyle & Erickson, 2008; Gil et al., 2015; Hanning et al., 2009; Pachepsky et al., 2011; Sapers & Jones, 2006; Suslow, 2010; Suslow et al., 2003). Chemical sanitizers applied during the washing process are important for inactivating pathogens on the produce, and preventing cross-contamination via the washwaters and cutting tools (Allende et al., 2008; FSAI, 2001; Gombas et al., 2017; Grandison, 2011; Luo et al., 2011). Further discussion of sanitizers will be addressed below. The

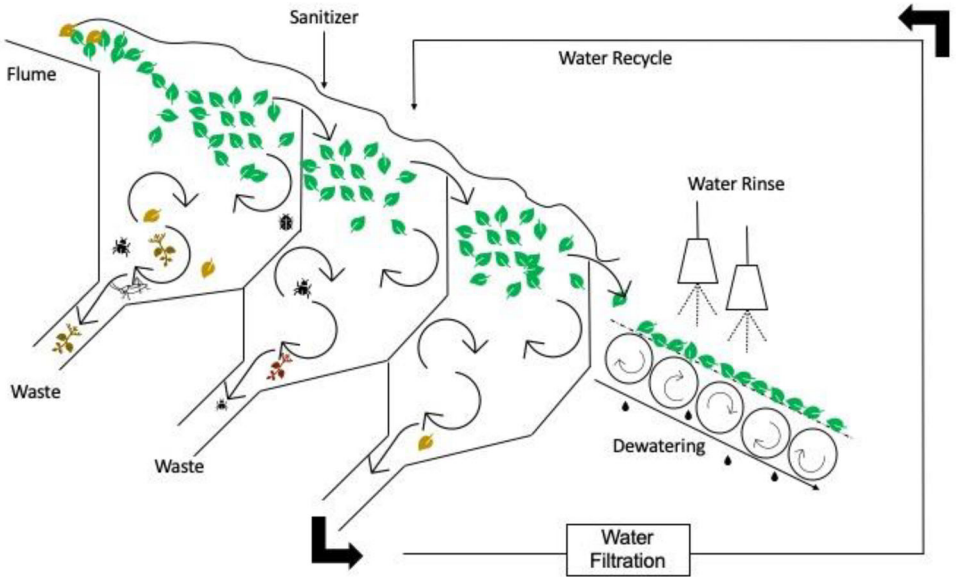

Figure 3. Schematic of a figurative triple washed process of leafy greens featuring, a flume, flotation washing system, and roller conveyor with a final rinsing step. This figure was an adaption of multiple published schematics (Grandison, 2011; López-Gálvez et al., 2019).

produce may then be rinsed, often by spraying with tap water, to remove sanitizer residues and reduce or maintain produce temperature (Gil et al., 2015; Gombas et al., 2017). To reduce water demand, washwaters can be recycled within the postharvest facility; typically effluents from later processing units are routed back to the influents of upstream washing units containing dirtier water (e.g., sending the effluent of the second tank back to the first immersion tank) (López-Gálvez et al., 2019; Tudela, López-Gálvez, Allende, & Gil, 2019; Tudela, López-Gálvez, Allende, Hernández, et al., 2019). A dewatering step involving centrifugation or forced air-bed conveyors can precede packaging using appropriate materials to enhance shelf-life (Gil et al., 2015; Jacxsens et al., 2003); packaging must maintain a proper gas composition that accounts for the continued respiration of produce on the shelf.

For meat and poultry processing, animals are inspected and then slaughtered, typically by stunning, hoisting by one leg, and severing an artery; the bleeding maintains carcass quality (Guo et al., 2015). Hides typically are removed. However, for poultry and pigs, where skin is consumed, a scalding process is performed involving immersion of carcasses in warm water (pigs at 57.7–61.0 °C for 3–8 min (Dickson et al., 2019), and chickens at 51–64 °C for 30–120 sec (FSIS, 2015)) to facilitate mechanical hair and feather removal. The scalding water may contain chemical sanitizers (USDA, 2019). Livestock animals (e.g., cattle and pork) are singed at 800–1000 °C

to remove dirt and fecal matter and lower the microbial load (Guo et al., 2015). Carcasses are then polished to remove burnt surfaces. Head removal and evisceration follows; evisceration can cause contamination by intestinal contents (Hill et al., 2010; Rossler et al., 2020). Carcasses are then split in half, dressed to remove organs such as the kidneys and visible contamination, and washed. This washing step is the primary step where chemical sanitizers may be applied (USDA, 2019). Prior to refrigerated storage, the meat is chilled, often by blast chilling (Guo et al., 2015), involving exposing animal cuts to cool air at −20 °C to −40 °C (Cano-Muñoz, 1991).

Seafood processing occurs immediately after harvest/capture, since seafood is more susceptible than meat to spoilage and contamination (Diler & Vácha, 2016). Seafood is usually chilled throughout the process between harvest and the final product. For example, European legislation in 2004 required that fish must be maintained at temperatures approaching that of melting ice (European Commission, 2004; Visciano et al., 2014). At higher temperatures, fish are prone to the production of histamines, which are implicated in scombroid fish poisoning (Mercogliano & Santonicola, 2019). Fish slaughtering involves stunning, bleeding, and descaling by mechanical means or cold pressure water jets (Diler & Vácha, 2016). Fish are then eviscerated, a critical step since visceral contents may contaminate the commodity (Codex Alimentarius Commission, 2000). The fish is then cut into portions (if relevant), washed, and packaged. Chemical sanitizers may be applied during the washing step. Chemical sanitizers are less active at the low temperatures at which seafood is processed.

There are several important differences between sanitization of food in postharvest washing facilities and drinking water disinfection. First, disinfectant contact times in drinking water facilities can be hours, with contact continuing within distribution systems conveying water to consumers. In contrast, total contact times with chemical disinfectants are approximately 1–5 min based on residence times in immersion tanks in postharvest produce washing facilities, with residuals removed by final rinse steps (López-Gálvez et al., 2019; Luo et al., 2012; Tudela, López-Gálvez, Allende, & Gil, 2019; Tudela, López-Gálvez, Allende, Hernández, et al., 2019; Zhou et al., 2015).

Second, in addition to the solid food, washwaters feature very high levels of dissolved organic matter that exerts a strong disinfectant demand. While dissolved organic carbon (DOC) is typically used to measure dissolved organic matter content in drinking water research (with levels typically $\leq$5 mg/L), chemical oxygen demand (COD) is used more frequently for research at postharvest washing facilities; COD may better reflect disinfectant demand. Weng et al. (2016) demonstrated that the release of juice from produce increased as the produce was chopped and particularly shredded

(Weng et al., 2016). For example, 2.3 mL/kg were released from whole baby spinach leaves, resulting in 48 mg/L COD (9.9 mg/L DOC) in the washwater. However, shredded romaine lettuce released 95 mL/kg of juice, contributing 2420 mg/L COD (690 mg/L DOC) to the washwater. There were also significant differences depending on the type of produce, with shredded carrots releasing 158 mL/kg of juice, resulting in 4530 mg/L COD (1780 mg/L DOC) in the washwater. These differences were observed at full-scale processing facilities, with 60 mg/L COD observed in a washwater handling whole leaf baby lettuce, but approximately 360 mg/L COD measured in washwater treating chopped or shredded lettuce (Tudela, López-Gálvez, Allende, & Gil, 2019; Tudela, López-Gálvez, Allende, Hernández, et al., 2019). The COD accumulates fairly rapidly. For example, over 5 hr, the COD increased from approximately 30 mg/L to approximately 110 mg/L in a facility washing whole baby lettuce leaves, from approximately 70 mg/L to approximately 300 mg/L in a system washing cut lettuce, and from approximately 500 mg/L to approximately 7000 mg/L in a system washing chopped carrots, onions, and tomatoes (López-Gálvez et al., 2019). Similarly, the COD increased from 130 mg/L to 390 mg/L over 4 h at a facility washing whole tomatoes (Zhou et al., 2015). This COD exerts rapid disinfectant demand (e.g., mostly within 5 min for chlorine) (Weng et al., 2016) on par with the short disinfectant contact times. Since many facilities are operated manually (Tudela, López-Gálvez, Allende, & Gil, 2019; Tudela, López-Gálvez, Allende, Hernández, et al., 2019), these high COD concentrations and their rapid changes can render it difficult to maintain consistent disinfectant exposures (Tudela, López-Gálvez, Allende, & Gil, 2019; Tudela, López-Gálvez, Allende, Hernández, et al., 2019; Zhou et al., 2015).

Third, despite some differences in treatment trains and the locations of disinfectant application (e.g., plant headworks, prefiltration, and postfiltration), drinking water treatment plants are fairly uniform, while postharvest food processing trains can be unique to each type of food. For example, one commercial facility washing leafy greens, carrots, onions, and tomatoes employed two 3000 L tanks in series fed by tap water at 3–4 °C (López-Gálvez et al., 2019). The water was treated with chlorine using calcium hypochlorite ($Ca(OCl)_2$) and sodium hypochlorite (NaOCl) to target 40–60 mg/L as Cl_2 free chlorine and citric acid to maintain the pH between 6.5 and 7.5; effluent from the second tank was recycled to the inlet to the first tank (López-Gálvez et al., 2019). The total contact time with washwater in the two tanks was only 30 sec, prior to a final rinse with tap water. The washwater COD increased to approximately 110 mg/L over 5 hr when treating whole baby lettuce leaves, but to approximately 7000 mg/L when treating shredded carrots, onions, and tomatoes (López-Gálvez et al., 2019). A facility washing tomatoes employed two 75,000 L tanks in series fed with

tap water at a total residence time of 1.5 min (Zhou et al., 2015); effluent from the second tank was recirculated to the first tank. The washwater temperature reached 42 °C and was treated with 390 mg/L as Cl_2 chlorine and citric acid to maintain the pH between 7 and 7.5. After the immersion tanks, the tomatoes were sprayed with a 5 mg/L chlorine dioxide solution and then packaged. These examples highlight the variation in treatment conditions, particularly temperature, which can have significant implications for the reactivity of disinfectants with respect to microorganisms and DBP production. These examples also indicate the rapid variation in COD, which can complicate efforts to maintain consistent disinfectant exposures.

4. Food sanitizers and marketability

Water washing to remove dirt and pesticide residues is coupled with sanitizers to inactivate pathogens and reduce the microbial loads that pose a threat to the quality and shelf-life of produce and meat (Gil et al., 2009). Food sanitization can be categorized into physical and chemical interventions. Physical sanitization techniques include heat, gamma irradiation, UV light, ultrasound, pulsed light, cold gas plasma, and high hydrostatic pressure (Ali et al., 2018; De Corato, 2020). Chemical sanitizers, applied in washwaters to food by sprays or immersion, include chlorine, ozone, chlorine dioxide, peracetic acid, and hydrogen peroxide (Aryal & Muriana, 2019; De Corato, 2020; Gombas et al., 2017).

Standards for application of sanitizers to food can be complex and diverse. For example, in the United States, the Environmental Protection Agency (EPA) oversees the application of sanitizers to control microorganisms in process washwater or on raw agricultural commodities, while the Food and Drug Administration (FDA) oversees sanitizer applications intended to control microorganisms in processed food (Gombas et al., 2017). Thus, one or both agencies may oversee sanitizer applications in postharvest washing facilities depending on the intended targets for sanitizer applications. Moreover, while application of chlorine to control microorganisms on produce is common in the United States and southern Europe, this practice is prohibited in certain northern European countries (e.g., Belgium, Denmark, Germany, the Netherlands, and Switzerland) following concerns over the production of halogenated byproducts (Nguyen et al., 2016; Rico et al., 2007).

4.1. Marketability concerns

Before discussing the impact of chemical disinfectants on microbial inactivation and DBP formation, it is important to note the potential impacts of

sanitizers on food quality. Just as applications of chemical disinfectants to conventional drinking waters must consider control of taste and odor compounds, postharvest food processing trains must consider the impacts of disinfection processes on product marketability. Food processing trains must maintain marketability over product shelf-lives (Grandison, 2011) ranging from 1 to 2 weeks at 0–1 °C at 95–100% humidity for ready-to-eat spinach to 1–8 months at −1–4 °C at 90–95% humidity for apples (Aked, 2002). Factors that affect marketability include formation or loss of pigment (e.g., loss of chlorophyll or browning), changes in flavor (e.g., decreasing acidity, increasing sweetness, or formation of flavor volatiles), and changes in texture (e.g., tissue softening or water loss) (Rico et al., 2007).

These changes could be fostered by natural processes, including ethylene production and increased respiration rates, but may also be impacted by food disinfection and processing (Aguayo et al., 2014). For instance, panelists tasting carrot sticks noted differences when the carrot sticks were washed with 200 mg/L as Cl_2 NaOCl, 30 mg/L as Cl_2 chlorine generated by electrolysis of 1 g/L NaCl, or 250 mg/L peracetic acid (PAA), but not when treated with 20 mg/L as Cl_2 NaOCl, 80 mg/L PAA, or 1 mg/L gaseous chlorine dioxide (ClO_2) (Vandekinderen et al., 2008). Exposure to ClO_2 decreased the red color of the carrots, while 250 mg/L PAA increased the yellow and red colors. Moreover, the treatments could degrade nutrient content. Treatment with 200 mg/L as Cl_2 NaOCl, 30 mg/L as Cl_2 chlorine generated electrochemically, or 1 mg/L gaseous ClO_2 decreased ζ-carotene by approximately 20–25%, while treatment with 200 mg/L NaOCl or 250 mg/L PAA decreased α-tocopherol (vitamin E) by approximately 50% and approximately 75%, respectively (Vandekinderen et al., 2008). Another study detected a greater decrease in vitamin C concentrations after baby spinach was treated with 80 mg/L PAA than with NaOCl added to achieve an approximately 3 mg/L as Cl_2 residual, but that the vitamin C concentrations declined in both cases to reach comparable levels after 8 days of storage (Gómez-López et al., 2013). Other studies have demonstrated that ozone can degrade antioxidants in foods, including β-carotene and ascorbic acid (Alexandre et al., 2018; Alothman et al., 2010; da Silva et al., 2015; de Jesus Benevides et al., 2011; Fatima et al., 2019; Fundo et al., 2018; Jackowska et al., 2019; Karaca & Velioglu, 2014, 2020; Lombardo et al., 2015; Taiye et al., 2020; Yeoh et al., 2014). Similarly, baby spinach leaves exposed to gaseous ozone at 0.1 g/m^3 levels started to discolor after two days of exposure (Shynkaryk et al., 2016), and treatment of chicken and duck breast meat with gaseous ozone resulted in lipid oxidation and discoloration (Muhlisin et al., 2016).

Hereafter this review focuses on chlorine and ozone with respect to microbial inactivation and DBP formation. Chlorine is the most widely

employed chemical sanitizer. In addition, the byproducts formed by reactions of these chemical sanitizers have received the most attention.

5. Microbial inactivation by chlorine and ozone

5.1. Chlorine

Chlorine is the most common chemical sanitizer applied in aqueous solutions to foods. Chlorine gas (Cl_2) is a strong oxidant ($E^0 = 1.39$ V; Eq. (1)). Chlorine gas is typically employed by the largest operations, since it is the least expensive form of chlorine, but also the most dangerous in terms of controlling leaks (Suslow, 1997). For smaller operations, $Ca(OCl)_2$ powder or tablets (~65% active ingredients) are used (Suslow, 1997). Alternatively, NaOCl, available in 5.25–12.75% by weight solutions, can be used, but shipping the liquid is expensive (Suslow, 1997). All of these forms of chlorine rapidly convert to hypochlorous acid (HOCl) or hypochlorite (OCl^-) in water (Eqs. (2)–(4)). All three forms remove two electrons from a target to form chloride (Eq. (5)); these oxidation reactions contribute to pathogen inactivation. A growing technology involves on-site generation of chlorine by electrochemical oxidation of high concentrations (e.g., 1 g/L) (Vandekinderen et al., 2008) of chloride (reverse of Eq. (1)) (Esua et al., 2020; USFDA, 2018). Facilities typically monitor total free chlorine, defined as the sum of Cl_2, HOCl, and OCl^-. However, because HOCl is a significantly more potent disinfectant than OCl^-, facilities typically maximize the occurrence of HOCl by adjusting pH to 5–7, below the 7.5 pK_a of HOCl (Eq. (6)), using citric or phosphoric acids (De Corato, 2020; Gómez-López et al., 2014; López-Gálvez et al., 2019; Luo et al., 2012; Shen et al., 2016; Suslow, 1997, 2001; Zhou et al., 2014). It is important to note that free chlorine will react with ammonia or organic amines to produce chloramines (e.g., NH_2Cl). Chloramines do not contribute significantly to microbial inactivation (Suslow, 1997). Moreover, microbial inactivation by chlorine increases with temperature, but many produce washing facilities (e.g., for leafy vegetables) cool washwaters to $< 10\,^{\circ}C$ to reduce spoilage (Zagory, 1999).

$$Cl_2 + 2\ e^- \rightarrow 2\ Cl^- \quad E^0 = 1.39\ V \tag{1}$$

$$Cl_2 + H_2O \rightarrow HOCl + H^+ + Cl^- \tag{2}$$

$$NaOCl \rightarrow Na^+ + OCl^- \tag{3}$$

$$Ca(OCl)_2 \rightarrow Ca^{2+} + 2\ OCl^- \tag{4}$$

$$HOCl\ (OCl^-) + 2\ e^- + H^+ \rightarrow Cl^- + H_2O\ (OH^-) \tag{5}$$

$$HOCl \leftrightarrow H^+ + OCl^- \quad pK_a = 7.5 \tag{6}$$

Despite more than 100 years of experience employing chlorine to control pathogens in drinking water, the detailed mechanisms responsible for

microbial inactivation remain poorly understood. Viruses consist of genomic material surrounded by a protein-based capsid associated with attachment to hosts and injection of genomic material into hosts. Wigginton et al. (2012) found that roughly half of the inactivation of bacteriophage MS2 was associated with chlorine reactions with the genome, with the remainder attributable to chlorine reactions with proteins involved in injection of the genome. By comparison, all of the inactivation of MS2 by chlorine dioxide was attributable to reactions with proteins involved in attachment to the host. For UV disinfection, 80% of the inactivation was associated with UV-mediated alterations to the genome, and the remainder to modifications to proteins involved with genome injection. A similar study evaluated inactivation of phage Phi6, an enveloped virus containing an outer lipid layer (Ye et al., 2018). While inactivation was associated with alterations to the genome during UV disinfection, damage to proteins dominated inactivation by chlorine.

Chlorine reactions alter genomic material by forming 8-chloro-adenine and 5-chloro-cytosine (Whiteman et al., 2002). Regarding proteins, chlorine reacts readily with 7 of the 20 common amino acids (cysteine, methionine, histidine, tryptophan, lysine, tyrosine, and arginine) with rate constants faster than with the peptide bonds linking the amino acids (Pattison and Davies, 2001). The predominant products have been identified for several of these amino acids, including cysteic acid (Hawkins et al., 2003), methionine sulfoxide (Hawkins et al., 2003), lysine nitrile (Sivey et al., 2013; Walse et al., 2009), 3-chlorotyrosine and 3,5-dichlorotyrosine (Choe et al., 2015), and 5 tryptophan-derived products (including 2 chlorinated products (Hua et al., 2020)). When bacteriophage MS2 was exposed to increasing chlorine doses, amino acids in the protein capsid were depleted in the order methionine > tryptophan > tyrosine > lysine, forming methionine sulfoxide at yields up to approximately 50%, 3,5-dichlorotyrosine at up to approximately 50% yields, and lysine nitrile at up to 30% yields (Choe et al., 2015). Covalent modifications to amino acid side chains alters their interactions within proteins, degrading secondary structure and function (Howell et al., 2015; Sivey et al., 2013). Unlike viruses, bacteria can repair oxidative damage, rendering it more difficult to characterize the pathways leading to inactivation. However, research has demonstrated that *Escherichia coli* features a heat-shock protein that enhances resistance to chlorine inactivation by clearing cytoplasmic proteins damaged by chlorine (Winter et al., 2008).

To inactivate pathogens and lower the overall microbial load, chlorine can be applied at numerous locations throughout the food processing train, from applications in the field just after harvest to cleaning processing equipment after use (Suslow, 2005). The Food and Agricultural Organization

(FAO) of the United Nations and WHO report free chlorine doses of 50–200 mg/L as Cl_2 for exposure times of 2–10 sec for cooling sprays applied during harvest (FAO/WHO, 2009). However, the main exposures are applied to produce using flumes, water dump tanks, spray washers, or hydrocoolers in postharvest washing facilities. Free chlorine doses of approximately 75–200 mg/L as Cl_2 for contact times of $\leq$ 5 min typically are applied to produce in the United States (Table 2) (Bao Loan et al., 2016; Cardador & Gallego, 2012; Francis et al., 1999; Fukayama et al., 1986; Huang & Batterman, 2009; Klaiber et al., 2005; Suslow, 1997, 2005). In the United States, lower concentrations are employed for red meat and poultry ($\leq$50 mg/L as Cl_2) and eggs ($\leq$60 mg/L as Cl_2) for shorter times ($\leq$2 min) (USDA, 2019). The Codex Alimentarius Commission of the FAO and WHO recommended 50 mg/L as Cl_2 for carcass and hide-removal sprays and 20–50 mg/L as Cl_2 for primal cut sprays, each for contact times of 3–5 sec to control *Salmonella* and *E. coli* (Codex Alimentarius Commission, 2011; FAO/WHO, 2016). Lower concentrations (10 mg/L as Cl_2) were recommended for fish, without recommendations regarding contact time (Codex Alimentarius Commission, 2000). After chlorine contact, food is typically rinsed to remove residuals, providing a firm limit to contact times (Gombas et al., 2017).

Although these doses are much higher than those applied to disinfect drinking water ($\sim$3 mg/L as Cl_2), the free chlorine residuals achieved may be much lower than the applied doses due to the high chlorine demand of the dissolved COD in washwater as well as reactions with the solid produce. Chlorine demand correlates with COD content and thus with the type of produce and degree to which it has been cut. For example, while whole baby spinach leaves exhibited 5–20 mg/L as Cl_2 free chlorine demand and produced $<$10 mg/L as Cl_2 of chloramines, shredded carrots exerted 350–650 mg/L as Cl_2 chlorine demand and produced 50–100 mg/L as Cl_2 chloramines (Weng et al., 2016). Since approximately 50–80% of the chlorine demand occurred within 5 min of contact (Weng et al., 2016), significant reductions in chlorine residual can occur despite the $\leq$5 min overall contact times in postharvest washing facilities. The rapid increase in COD within washwaters makes it challenging to maintain consistent residuals. For example, at a commercial vegetable washing facility the free chlorine residual remained at 50–70 mg/L as Cl_2 over 5 hr while washing whole baby lettuce leaves (maximum COD of $\sim$110 mg/L), but fluctuated from approximately 40–250 mg/L as Cl_2 over 3 hr when treating shredded carrots, onions, and tomatoes (maximum COD $\sim$7000 mg/L) (López-Gálvez et al., 2019). Similarly, at a facility washing tomatoes, the COD increased from 130 to 390 mg/L over 4 hr, such that the 350 mg/L as Cl_2 chlorine applied to the first immersion tank (and adjusted manually) dropped to a 100 mg/L as Cl_2 residual within 4 h. Measurement of chlorine residual using

Table 2. Examples of conditions and antimicrobial efficacies for chlorine treatment of food.

Chlorine

Food type	Pathogen	Contact time (min)	pH	Temperature	Dose (mg/L as Cl_2)	Log reduction	Reference
Shredded Lettuce	*L. monocytogenes*	10	9.2	4 °C	200	1.3	Zhang and Farber (1996)
			9.3	22 °C		1.7	
Iceberg Lettuce	*E. coli* O257:H7	2	8.0	22 °C	20	0.5	Keskinen et al. (2009)
					200	0.8	
			2.6		50	0.7	
Romaine Lettuce			8.0		20	0.5	
					200	0.6	
			2.6		50	0.5	
Head Lettuce	*E. coli* O257:H7	1	9.3	20 °C	200	0.9	Koseki et al. (2003)
	Salmonella spp.					1.0	
Beef	*E. coli* K12	2	3.0	–	34	0.6	Arya et al. (2018)
Pork				–		0.8	
Pork	*E. coli* O157:H7	5	2.5	23 °C	50	2.0	Rahman et al. (2013)
Trout	*E. coli* O257:H7	1	2.3	22 °C	38	1.0	Al-Holy and Rasco (2015)
	Salmonella Typhimurium					1.0	
	L. monocytogenes					1.0	
Chicken	*E. coli* O257:H7					1.0	
	Salmonella Typhimurium					1.0	
	L. monocytogenes					1.0	
Beef	*E. coli* O257:H7					1.0	
	Salmonella Typhimurium					1.0	
	L. monocytogenes					1.0	

oxidation-reduction potential (ORP) monitors does not accurately distinguish free chlorine residual concentrations, with similar ORP levels detected for 1–3 mg/L as Cl_2 chlorine residuals (Gómez-López et al., 2014). The rapid variation in COD concentrations can make it challenging for facilities to maintain consistent disinfectant exposures when disinfectant doses are adjusted manually. Research at a lettuce processing facility demonstrated that incorporation of automatic controllers significantly improved the ability to maintain a consistent chlorine residual and pH (Tudela, López-Gálvez, Allende, & Gil, 2019; Tudela, López-Gálvez, Allende, Hernández, et al., 2019).

Many studies have investigated the inactivation by chlorine of pathogens inoculated onto produce under simulated processing conditions in the lab or in pilot-plant studies (Al-Holy & Rasco, 2015; Arya et al., 2018; Bolten et al., 2020; Gil et al., 2009; Gómez-López et al., 2014; Keskinen et al., 2009; Koseki et al., 2003; López-Gálvez et al., 2010, 2019; Luo et al., 2012, 2018, 2011; Shen, 2014; Sohaib et al., 2016; Tomás-Callejas et al., 2012; Tudela, López-Gálvez, Allende, & Gil, 2019; Tudela, López-Gálvez, Allende, Hernández, et al., 2019; Van Haute et al., 2015; Zhang & Farber, 1996; Zhou et al., 2014, 2015). Table 2 provides an abridged list of chlorine antimicrobial efficacies against pathogens on vegetables, meat, poultry, and seafood. Noteworthy is the low log-removal (maximum of 2-log removal) achieved despite much higher applied chlorine doses than used in drinking water. For example, in a study on the antimicrobial efficacy of chlorine against *L. monocytogenes* on inoculated shredded lettuce (5×2 cm coupons) at pH 9.2 and at 4 °C and 22 °C, a 200 mg/L as Cl_2 wash for 10 min achieved 1.3- and 1.7-log reductions, respectively (Zhang & Farber, 1996). Similarly, a 200 mg/L as Cl_2 application of free chlorine to romaine lettuce only produced a 0.6-log reduction of *E. coli* O157:H7 after a 2 min wash at pH 8.0 and 22 °C (Keskinen et al., 2009). While the high chlorine doses must be weighed against the short contact times, a 200 mg/L as Cl_2 residual over a 2 min contact time would represent a 400 mg•min/L exposure, substantially higher than the approximately 200 mg•min/L exposures employed for primary drinking water disinfection (USEPA, 1999). Of course, rapid chlorine consumption by COD would reduce the chlorine residual and may partially explain the relatively low inactivation despite the high chlorine dose. However, the same study found comparable log-removal of *E. coli* (0.5-log) when 20 mg/L as Cl_2 was applied at pH 8.0 or 50 mg/L as Cl_2 was applied at pH 2.6 as when 200 mg/L as Cl_2 was applied at pH 8.0 (Keskinen et al., 2009; Table 2). The comparable inactivation despite order of magnitude differences in chlorine dose suggests that a fraction of the *E. coli* was inaccessible to chlorine (e.g., by being located within produce crevices) (Codex Alimentarius Commission, 2011).

Research has indicated that free chlorine is more effective for preventing microbial transfer between produce via the washwater (i.e., cross-

contamination) than for inactivating microorganisms on produce surfaces. For example, one study employed a pilot system containing two wash tanks to wash shredded iceberg lettuce mixed with whole spinach leaves at 0.2% of the shredded lettuce (Luo et al., 2012). Only the spinach was inoculated with 4.9-log colony forming units (CFU)/g *E. coli* O157:H7. The washwater was spiked with NaOCl to achieve a 20 mg/L as Cl_2 residual, but rapidly decreased to nondetectable levels within 12 min. When chlorine was re-spiked every 12 min over 36 min to reach a 20 mg/L as Cl_2 residual, higher doses were required each time, because the COD increased from 300 mg/L to 1600 mg/L over the 36 min. As long as the chlorine residual remained $>$ 1 mg/L as Cl_2, *E. coli* O157:H7 was not observed in the washwater or the lettuce. Near 1 mg/L as Cl_2 residual, *E. coli* O157:H7 was detected on the lettuce, but not the washwater, suggesting transfer by physical contact between the spinach and lettuce. However, only approximately 0.8-log CFU/g decrease in *E. coli* O157:H7 was measured over the 36 min period on the spinach. Other research with simulated washwater containing spinach juice indicated that a 3 mg/L as Cl_2 residual was needed to inactivate *E. coli* O157:H7 spiked into the washwater to nondetectable levels (Gómez-López et al., 2014). The difficulty associated with inactivation of bacteria on produce surfaces may result from restricted access of chlorine to the bacteria when they are located within crevices or attached to cut surfaces.

There are also differences in the susceptibility of native microbial populations to inactivation between different produce types. When cut lettuce, cut red cabbage or chopped onion was exposed to 10 mg/L as Cl_2 free chlorine, approximately 6–7-log inactivation of native total aerobic bacteria (TAB) was achieved, but only approximately 3-log inactivation was observed for whole baby leaf lettuce (Tudela, López-Gálvez, Allende, & Gil, 2019; Tudela, López-Gálvez, Allende, Hernández, et al., 2019). The lower inactivation on whole baby leaf lettuce may be associated with a greater resistance of the native microbiome resulting from its prior exposure to harsh conditions on leaf surfaces (e.g., sunlight exposure) (Gruzdev et al., 2011). As a result, the FAO and WHO recognize chlorine as an effective antimicrobial to prevent cross-contamination of produce via the washwater, but not inactivation of the microbes already on food surfaces (FAO/WHO, 2009).

5.2. Ozone

Ozone (O_3) is a stronger oxidant than chlorine ($E^0 = 2.07$ V; Eq. (7)). Ozone is produced on-site by passing air or pure oxygen gas (O_2) through ultraviolet (UV) light ($<$ 210 nm) or a high voltage corona discharge ($>$5000 V) to split O_2 to oxygen atoms; O atom combination with O_2 produces O_3 (Eq. (8)) (Esua et al., 2020; Suslow, 2004). While chlorine is

applied as an aqueous solution to produce, O_3 can be applied either directly as a gas or as an aqueous solution generated by bubbling O_3 gas through water.

$$O_3 + 2H^+ + 2\ e^- \rightarrow O_2 + H_2O \quad E^0 = 2.07\ V \tag{7}$$

$$O + O_2 \rightarrow O_3 \tag{8}$$

Ozone is much less stable in water than chlorine, and can undergo autodecomposition initiated by reactions with hydroxide or reduced metals (Eqs. (9) and (10)). Thereafter, decomposition of $HO_3^\bullet$ produces hydroxyl radical ($^\bullet$OH; Eqs. (12) and (13)). Hydroxyl radical reaction with O_3 generates $HO_2^\bullet$ (Eq. (14)), whose conjugate base ($O_2^{\bullet-}$) propagates chain decomposition of O_3 via Eq. (10). Each cycle (Eqs. (10) and (12)–(14)) depletes two O_3 molecules while generating one $^\bullet$OH. Although $^\bullet$OH is a strong oxidant, O_3 is a more effective disinfectant. Hydroxyl radical is not very selective in its reactions with biomolecules (NIST, 2002), such that much of its oxidizing power may be wasted on oxidation of biomolecules less critical for pathogen survival. Reactions of organic matter (R-H) with $^\bullet$OH can expedite chain decomposition of O_3 via Eqs. (15) and (16), and thence Eq. (10). In drinking waters, applied O_3 doses of up to 3 mg/L are depleted within 20 min (Linden et al., 2015; Plumlee et al., 2014; Suslow, 2004), and even faster (e.g., <2 min) in waters with higher organic matter concentrations. Given the high organic loads in postharvest processing facility washwaters, rapid depletion of aqueous O_3 concentrations is expected.

$$O_3 + OH^- \rightarrow HO_2^\bullet + O_2^{\bullet-} \tag{9}$$

$$O_3 + O_2^{\bullet-} \rightarrow O_2 + O_3^{\bullet-} \tag{10}$$

$$Me^{n+} + O_3 \rightarrow Me^{n+1} + O_3^{\bullet-} \tag{11}$$

$$O_3^{\bullet-} + H^+ \rightarrow HO_3^\bullet \tag{12}$$

$$HO_3^\bullet \rightarrow {}^\bullet OH + O_2 \tag{13}$$

$$O_3 + {}^\bullet OH \rightarrow HO_2^\bullet + O_2 \tag{14}$$

$$R{-}H + {}^\bullet OH \rightarrow H_2O + RO_2^\bullet \tag{15}$$

$$RO_2^\bullet \rightarrow R^+ + O_2^{\bullet-} \tag{16}$$

The mechanisms by which ozone inactivates pathogens have received less attention than for chlorine. However, when bacteriophage MS2 was treated with ozone, degradation of methionines in the protein capsid occurred at comparable doses (on a molar basis) as with chlorine (Choe et al., 2015). However, tyrosines and tryptophans were more reactive, while lysines were less reactive. For three model proteins, loss of protein second structure by ozone occurred at comparable molar doses to those of chlorine (Choe et al., 2015).

Table 3. Examples of conditions and antimicrobial efficacies for ozone treatment of food.

Ozone							
Food type	Pathogen	Contact time (min)	pH	Temperature	Dose (mg/L O_3)	Log reduction	Reference
Shredded Lettuce	*Shigella sonnei*	5	6.7	–	2.0	1.4	Selma et al. (2007)
				–	5.0	1.8	
Shredded Lettuce	*E. coli* O157:H7	10	–	22 °C	10	1.5	Singh et al. (2002)
Baby Carrots			–			1.7	
Raspberries	*E. coli* O157:H7	16	–	20 °C	7.6	2.7	Bialka and Demirci (2008)
	Salmonella spp.		–			2.7	
Strawberries	*E. coli* O157:H7		–			1.8	
	Salmonella spp.		–			1.8	
Bell pepper	*E. coli* O157:H7	30	–	18–20 °C	9 (gaseous)	2.3	Alwi and Ali (2014)
	Salmonella enterica sv.		–			2.1	
	L. monocytogenes		–			2.4	
Bighead croaker	Total viable counts	3 (days)	–	−1.5 °C (iced slurry)	0.1–0.2	1.4–2.0	Chen et al. (2016)
Salmon	*L. innocua*	1	–	4 °C	1–1.5	0.4–1.2	Crowe et al. (2012)
	Aerobic plate counts		–			0.3–1.0	
Pork	*E. coli* O157:H7	5	6.6	23 °C	5.2	1.0	Rahman et al. (2013)
Beef hides	*Enterobacteriaceae*	0.2	–	15 °C	2 (spray 4800 kPa)	3.4	Bosilevac et al. (2005)
	Aerobic plate counts		–			2.1	

Ozone requires much lower CT than chlorine to achieve inactivation of many pathogens in drinking water. For example, 2-log inactivation of *Cryptosporidium parvum* requires approximately 5000 mg•min/L CT for chlorine, but approximately 5 mg•min/L CT for ozone (NRC, 2012). Similarly, 2-log inactivation of *E. coli* requires approximately 1 mg•min/L CT for chlorine, but approximately 0.01 mg•min/L CT for ozone (NRC, 2012). Several reviews summarize ozone inactivation of pathogens and other microbes on fruits, vegetables, meats, poultry, and seafood (Brodowska et al., 2018; Esua et al., 2020; Meireles et al., 2016). Table 3 provides examples of log inactivation values achieved during ozonation of produce, meat and seafood. As for chlorination, log inactivation values during ozonation of food tend to be lower than expected relative to drinking water. For example, application of 5.2 mg/L aqueous O_3 to pork for 5 min achieved 1.0-log inactivation of *E. coli* O157:H7 (Selma et al., 2007). Similarly, a 10 mg/L ozone dose applied for 10 min to shredded lettuce and baby carrots achieved 1.5- and 1.7-log inactivation of *E. coli* O157:H7, respectively (Table 3) (Suslow, 2004). However, deionized water washes of the same produce achieved 1.1- and 1.2-log inactivation, respectively, suggesting that physical rinsing, not O_3, was responsible for most of the reduction in *E. coli* load. The importance of physical removal is further suggested by the 0.3–1.0 log removal of aerobic plate count bacteria when salmon was treated with 1.0–1.5 mg/L aqueous O_3 for 1 min (Crowe et al., 2012), but 2.1-log removal of aerobic plate count bacteria when 2 mg/L O_3 was sprayed on beef hides at 4800 kPa for 0.2 min (Table 3) (Bosilevac et al., 2005).

While permitted for food processing and storage, the U.S. EPA and FDA have not established limits on applied O_3 doses (Sohaib et al., 2016). Many of these doses applied to produce are higher than the $\leq$3 mg/L typically applied to drinking water. Although reaction with organic matter probably depleted the O_3 concentrations when applied to food, it is likely that the CT achieved was higher than the approximately 0.01 mg•min/L CT associated with 2-log inactivation of *E. coli* in drinking water (NRC, 2012). The stark differences in inactivation achieved for different foods treated with the same O_3 concentrations for the same contact times suggest that differences in food surface structures play a role in hindering O_3 accessibility to the pathogens. For example, application of 7.6 mg/L O_3 for 16 min achieved 2.7-log inactivation of *E. coli* O157:H7 on raspberries, but 1.8-log inactivation on strawberries, and 2.7-log inactivation of *Salmonella* spp. on raspberries, but 1.8-log inactivation on strawberries (Tomás-Callejas et al., 2012). These results suggest that pathogens on strawberry surfaces are less accessible to inactivation by O_3 than they are on raspberry surfaces. Although application of gaseous O_3 might be expected to enhance O_3 accessibility to pathogens on produce surfaces, the 2.9-log inactivation of

E. coli O157:H7 on bell peppers achieved by application of 9 mg/L gaseous O_3 (Alwi & Ali, 2014) was similar to the 2.7-log inactivation observed with 7.6 mg/L aqueous O_3 applied to raspberries (Tomás-Callejas et al., 2012). As for chlorine, these results suggest that a fraction of microbes on food surfaces is resistant to inactivation by O_3.

However, like chlorine, treatment of washwater with O_3 may be useful for preventing cross-contamination, thereby reducing water supply costs by enabling several cycles of washwater reuse (Selma et al., 2007). Ozone application during storage also may be useful for maintaining marketability by preventing microbial proliferation and rot (Brodowska et al., 2018). For example, fish stored in a refrigerator with a 1:1 slurry of ice with a 0.1–0.2 mg/L aqueous O_3 solution exhibited a 1.4–2.0 log reduction in total viable counts (i.e., bacteria, molds, and yeasts) and a 9-day extension of product shelf life (Chen et al., 2016). Similarly, gaseous O_3 helped to prevent the spread of pink rot (*Phytophthora erythrospetica*) in potatoes (Doona et al., 2010). Given its rapid depletion, O_3 must be applied continuously if maintenance of a residual is desired for storage. Alternatively, O_3 treatment during processing can be followed by addition of chlorine to maintain a residual for storage, since chlorine depletion is slower (NRC, 2012; Strickland et al., 2010). This exposure to different disinfectants may enhance microbial control since different microbes have different susceptibilities to inactivation by different disinfectants (NRC, 2012; Suslow, 2004). In addition to its relatively high activity as a disinfectant (at least for controlling cross-contamination), and for maintaining product shelf-life, there is interest in O_3 for food processing due to its lower production of halogenated byproducts, as discussed below.

6. Disinfection byproducts

6.1. Chlorine

Starting in the early 1900s, chlorinating potable water supplies dramatically reduced the incidence of waterborne diseases, such as cholera, listeria, and typhoid (Li & Mitch, 2018). However, in the 1970s, analytical chemists discovered trihalomethanes (THMs) at concentrations of up to 160 µg/L as byproducts of chlorine reactions with natural organic matter (NOM) in drinking water (Li & Mitch, 2018; Rook, 1974). Shortly thereafter, toxicologists and epidemiologists discovered an association between water chlorination and bladder cancer occurrence, with halogenated byproducts suspected to drive the risk (Li & Mitch, 2018). The US EPA has regulatory limits on only 11 DBPs in drinking water: $\leq$ 80 µg/L for the sum of 4 trihalomethanes (THMs; chloroform, bromodichloromethane, dibromochloromethane, and bromoform), $\leq$60 µg/L for the sum of 5 haloacetic acids

(HAAs; chloroacetic acid, bromoacetic acid, dichloroacetic acid, dibromoacetic acid, and trichloroacetic acid), ≤ 1 mg/L chlorite and ≤ 10 µg/L bromate (USEPA, 2020). California has a 0.8 mg/L Notification Level for chlorate, (California Water Boards, 2020) and a 6 µg/L Maximum Contaminant Level (MCL) for perchlorate in drinking water (California Water Boards, 2007). Much of the research related to DBPs associated with chlorine sanitization of food in postharvest washing facilities has focused on the same small molecule DBPs that have been the focus of drinking water research.

6.1.1. Chlorate, perchlorate, and bromate

The European Union (EU) is developing a maximum residual level (MRL) for chlorate on produce (European Commission Directorate-General for Health and Food Safety, 2020). While the final limit is likely to be higher than the extremely low default limit of 0.01 mg/kg, the potential regulatory limit is raising concerns over use of chlorine or chlorine dioxide as sanitizers, since both disinfectants are associated with chlorate production. The following discussion focuses on chlorate related to chlorine disinfection.

Chlorate has been associated primarily with NaOCl and $Ca(OCl)_2$ stock solutions via reactions with hypochlorite (OCl^-; Eq. (17)) (Adam & Gordon, 1999), not with systems employing chlorine gas (Cl_2) (Stanford et al., 2011). The reaction proceeds via two steps (Eqs. (18) and (19)), but is second-order in OCl^- because the first step, which generates chlorite (ClO_2^-) as a steady-state intermediate, is rate-limiting. Hypochlorite also decays via a slower reaction to release oxygen (Eq. (20)). Since the oxygen-producing reaction can be catalyzed by transition metals, NaOCl stock solutions are frequently filtered to remove transition metal-containing solids (Stanford et al., 2011). Hypochlorite stock solutions are also maintained at pH 11–13, because decay is faster at lower pH via Eq. (21) (Adam & Gordon, 1999). Chlorine oxidation of chlorate forms perchlorate (ClO_4^-; Eq. (22)), while OCl^- can oxidize bromide to bromate (BrO_3^-) (Eq. (23)) (Stanford et al., 2011).

$$3\ OCl^- \rightarrow\ ClO_3^- + 2Cl^- \tag{17}$$

$$2\ OCl^- \rightarrow\ ClO_2^- + Cl^-\quad k = 7.7 \times 10^{-9}\ M^{-1}s^{-1} \tag{18}$$

$$OCl^- + ClO_2^- \rightarrow\ ClO_3^- + Cl^-\quad k = 1.5 \times 10^{-6}\ M^{-1}s^{-1} \tag{19}$$

$$2\ OCl^- \rightarrow\ O_2 + 2\ Cl^-\quad k = 9.0 \times 10^{-10}\ M^{-1}s^{-1} \tag{20}$$

$$HOCl + 2\ OCl^- \rightarrow\ ClO_3^- + 2\ Cl^- + 2\ H^+ \tag{21}$$

$$OCl^- + ClO_3^- \rightarrow\ ClO_4^- + Cl^- \tag{22}$$

$$3\ OCl^- + Br^- \rightarrow\ BrO_3^- + 3\ Cl^- \tag{23}$$

Hypochlorite stock solutions (~13% by weight) can be obtained as bulk solutions from suppliers, or can be generated by dissolving $Ca(OCl)_2$ pellets

Table 4. Disinfection Byproducts (DBPs) in chlorinated foods.

Food	Treatment conditions	DBP class & concentration	Reference
Chopped/shredded vegetables	Store-bought in Italy	THMs: 26–144 μg/kg	Coroneo et al. (2017)
Salads and spinach	Store-bought in Spain	HAAs: <0.4–24 μg/kg	Cardador and Gallego (2012)
Lettuce mixes	Store-bought in Belgium	3-Chlorotyrosine: 4.5 mg/kg	Bao Loan et al. (2016)
Baby leaf mix	Chlorine: 40–60 mg/L as Cl_2; Contact time: 30 sec; pH: 4.2–8.3; Temperature: 4–6.5 °C; COD: 74 mg/L Tap water rinse	Chlorate: 34–240 μg/kg THMs: 4.2–41 μg/kg	López-Gálvez et al. (2019)
Fresh-cut lettuce	Same as above COD: 305 mg/L	Chlorate: 42–186 μg/kg THMs: 3.7–22 μg/kg	López-Gálvez et al. (2019)
Shredded vegetables	Same as above COD: 7090 ± 24 mg/L	Chlorate: 43–79 μg/kg THMs: 43–79 μg/kg	López-Gálvez et al. (2019)
Baby spinach	Chlorine: 3.5 mg/L as Cl_2; Contact time: 1 min; pH: 6.8; Temperature: 7 °C; COD: 474 mg/L	THMs: (washwater) 194 μg/L (after washing) 7 ± 1 μg/g (after rinsing) ND	Gómez-López et al. (2013)
Chopped/shredded lettuce or baby lettuce	Chlorine: 10–60 mg/L as Cl_2; Contact time: 60 sec; pH: approximately 5.5–8.5; Temperature: 6 °C	Chlorate: 0.05–2.0 mg/kg	Tudela, López-Gálvez, Allende, and Gil (2019)
Cut Lettuce	Chlorine: 95 mg/L as Cl_2; Contact time: 15 min; pH: 6; Temperature: 5 °C Tap water rinse	THMs: 490 μg/kg HAAs: 445 μg/kg Chloral hydrate: 23 μg/kg Dichloroacetamide: 62 μg/kg	Lee and Huang (2019)
Shredded spinach/lettuce	Chlorine: 100 mg/L as Cl_2; Contact time: 15 min; pH: 7; Temperature: 21 °C	3-Chlorotyrosine: 1.0–6.5 mg/kg 3,5-Dichlorotyrosine: 0–6.3 mg/kg Total small molecule DBPs: 4–12 mg/kg[a]	Komaki et al. (2018)

[a]Measured in the washwater, but converted to equivalent concentrations on the lettuce to facilitate comparison.

(Stanford et al., 2011). Alternatively, on-site generators can produce low-strength OCl^- stocks by electrolysis of chloride or higher strength stocks by generating Cl_2 gas and bubbling this through NaOH solutions (Stanford et al., 2013). Surveys of OCl^- stock tanks at drinking water facilities found ClO_3^- at 15–270 μg/mg free available chlorine (FAC) and ClO_4^- at 1–520 ng/mg FAC (Stanford et al., 2011), with no difference between methods of stock formation. However, while BrO_3^- was measured at approximately 0.1–0.2 μg/mg FAC in stock solutions delivered from suppliers or generated by dissolution of $Ca(OCl)_2$, up to 0.8 μg/mg FAC was measured in stocks formed by on-site generators, likely due to electrolytic oxidation of bromide in the brines used to generate chlorine (Stanford et al., 2011). To reduce levels of these byproducts in stock tanks, utilities can dilute the stock solutions to minimize the second-order degradation reaction

(Eqs. (17)–(19)), but they should ensure that the pH remains at 11–13 to reduce the rate of degradation via Eq. (21) (Breytus et al., 2017; Stanford et al., 2011). Refrigerating the stock tank can also reduce byproduct formation, and since these products accumulate over time, stock tanks should be sized to reduce the time between stock shipments. Stock solutions should be filtered to minimize transition metals (Breytus et al., 2017; Stanford et al., 2011). Although transition metal-catalyzed OCl^- degradation does not form ClO_3^- (Eq. (20)), the loss of OCl^- increases the levels of byproducts delivered to the water by necessitating a higher flowrate of stock solution to deliver the same level of free chlorine residual (Breytus et al., 2017; Stanford et al., 2011). Lastly, high purity NaCl solutions should be used for on-site chlorine generation to minimize bromate formation from bromide (Stanford et al., 2011).

A commercial lettuce washing facility observed no ClO_3^- when Cl_2 gas was used (Tudela, López-Gálvez, Allende, & Gil, 2019; Tudela, López-Gálvez, Allende, Hernández, et al., 2019). However, when NaOCl was used, ClO_3^- concentrations in washwater increased up to 15 mg/L in concert with the increase in COD up to 2500 mg/L; ClO_3^- concentrations on the lettuce reached approximately 2 mg/kg with little reduction after rinsing with tap water (Table 4; Tudela, López-Gálvez, Allende, & Gil, 2019; Tudela, López-Gálvez, Allende, Hernández, et al., 2019). Another commercial facility employing a combination of $Ca(OCl)_2$ and NaOCl observed that ClO_3^- concentrations in washwater and on produce were higher with higher washwater COD (López-Gálvez et al., 2019). Chlorate reached 1.2 mg/L in washwater associated with baby lettuce (~110 mg/L maximum COD) and approximately 200–300 µg/kg on the lettuce, but 2.7 mg/L in washwater from washing cut lettuce (~300 mg/L maximum COD) and 100–250 µg/kg on the lettuce (López-Gálvez et al., 2019). The increase in ClO_3^- concentrations may relate to an increase in loading from the chlorine stock tanks resulting from the higher chlorine dosing needed to achieve the target residual chlorine in the presence of higher washwater COD. The effect of a tap water rinse was inconsistent; for example, the tap water rinse for baby lettuce reduced chlorate to as low as 34 µg/kg during one sample event, but chlorate remained at 240 µg/kg during another event (Table 4). The limited reduction in ClO_3^- after the tap water rinse indicated uptake of ClO_3^- into the produce. Garrido et al. (2019) demonstrated that this uptake was 1% for chopped iceberg lettuce, 3% for baby spinach, 5% for baby lettuce and 8.5% for shredded carrots (Garrido et al., 2019). For lettuce and spinach, uptake was correlated with water uptake, potentially via stomata or intercellular spaces. For shredded carrots, uptake was higher than water uptake, suggesting molecular diffusion of ClO_3^- into the internal tissue. Chlorate uptake increased with produce cutting and as the wash time increased from 1 to 2 min.

6.1.2. Low molecular weight halogenated organic DBPs

Detailed mechanisms responsible for the formation of various low molecular weight DBP classes have been reviewed (Shah & Mitch, 2012). Analyses of 115 samples of ready-to-eat chopped garlic, shredded lettuce, chopped parsley and carrots from Italian grocery stores detected 26–144 μg/kg THMs (Table 4) (Coroneo et al., 2017). Similar analyses of Spanish salad and spinach typically measured approximately 1–5 mg/kg HAAs (Table 4) (Cardador & Gallego, 2012). In both cases, bromine-containing THMs and HAAs, which tend to be more toxic (Wagner & Plewa, 2017), were detected at lower concentrations than their fully chlorinated analogues (e.g., chloroform).

When a simulated washwater concocted by sequential additions of lettuce juice (maximum COD 1130 mg/L) was spiked with 80 mg/L as Cl_2 chlorine five times, HAAs accumulated to approximately 2100 μg/L (Shen et al., 2016) Although THM concentrations reached a maximum of approximately 860 μg/L, they fluctuated in concert with free chlorine residual, presumably decreasing when losses by volatilization outpaced formation from reactions of chlorine with the lettuce juice. A similar study found that THM and HAA concentrations varied with COD, but also with the type of produce (Tudela, López-Gálvez, Allende, Hernández, et al., 2019). THMs ranged from 40 to 300 μg/L and HAAs from 50 to 200 μg/L for whole baby leaf and cut lettuce (900 mg/L COD maximum), but 500 μg/L THMs and 700 μg/L HAAs were detected in washwater from chopped onions (3500 mg/L COD maximum). However, despite a lower COD (2500 mg/L maximum), THMs and HAAs reached 1700 μg/L and 3800 μg/L, respectively, for washwater from cut red cabbage. Many of these concentrations are orders of magnitude higher than the regulatory limits for THMs (80 μg/L) and HAAs (60 μg/L) in U.S. drinking waters. At a commercial processing facility, 34–54 μg/L THMs were detected in washwater associated with baby lettuce leaves or cut lettuce, while 2600 μg/L THMs were detected in washwater from shredded carrots, onions, and tomatoes; in all cases the tap water rinse reduced levels detected on the final produce to approximately 3–20 μg/kg THMs (Table 4) (López-Gálvez et al., 2019). These results indicate that rinsing may be more effective for removing THMs than chlorate.

Recent toxicological studies have demonstrated that halogenated acetaldehydes, haloacetonitriles, and haloacetamides can feature orders of magnitude higher cytotoxicity and genotoxicity in Chinese hamster ovary (CHO) cells than the THMs and HAAs regulated in drinking water (Wagner & Plewa, 2017). While these unregulated classes typically form at lower concentrations than regulated THMs and HAAs in drinking water (Li & Mitch, 2018), a study contacting cut lettuce with 100 mg/L as Cl_2 chlorine for 15 min at 5 °C measured 25 μg/L THMs and 222 μg/L HAAs, but 36 μg/

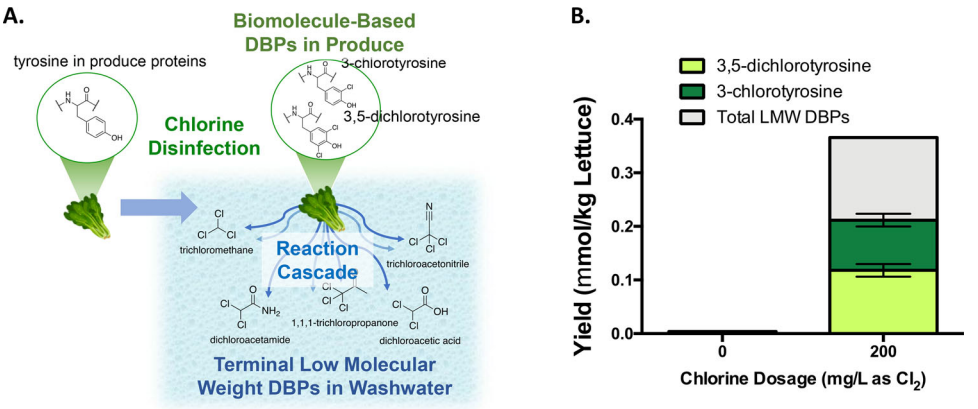

Figure 4. (A) Chlorination of protein-based tyrosines in lettuce initially forms chlorotyrosines that remain in the lettuce. Further reactions form low molecular weight (LMW) DBPs that disperse with the washwater. (B) Yields of chlorotyrosines and total LMW DBPs after chlorination for 15 min of 1 g shredded butterhead lettuce leaves at pH 7 at 21 °C. Chlorotyrosines were detected in the leaf phase, while volatile DBPs were measured in the aqueous phase. All DBP masses were normalized by the wet weight of leaf precursor material to facilitate the comparison of DBP yields. LMW DBPs included: dichloroacetamide, dichloroacetonitrile, trichloroacetonitrile, trichloroacetamide, chloroform, 1,1-dichloropropanone, and 1,1,1-trichloropropanone. Adapted from Komaki et al. (2018).

L trichloroacetaldehyde, 80 µg/L dichloroacetonitrile, and 50 µg/L dichloroacetamide (Lee & Huang, 2019). The same study detected 490 µg/kg THMs, 445 µg/kg HAAs, 23 µg/kg trichloroacetaldehyde, 62 µg/kg dichloroacetamide, but no dichloroacetonitrile on the lettuce (Table 4).

6.1.3. Biomolecule-based DBPs

The focus on low molecular weight DBPs in drinking water research results from the ease of their analysis and the tendency for even volatile DBPs to remain in drinking water within enclosed drinking water distribution systems. However, research with models for the natural organic matter (NOM; e.g., humic acids) precursors in drinking waters has demonstrated that these DBPs typically form over the long timescales relevant to distribution systems at yields <1% as the final products of a series of transformation reactions (Li & Mitch, 2018). The poorly characterized nature of NOM precursors has hindered the identification of the initial transformation products that may form at higher yields. However, the biomolecular precursors in food are well-characterized, and the initial chlorine reaction products are likely to be important during food sanitization given the short (<5 min) chlorine contact times. For example, chlorination of *N*-acetyltryptophan as a model for protein-bound tryptophan indicated formation of halogenated tryptophan intermediate products at up to 11% molar yield over a 15 min timescale, much higher than the total yield of low molecular

weight DBPs (Hua et al., 2020). Over a 24-hr timescale these intermediate biomolecule-based DBPs fragmented to release the low molecular weight DBPs of interest in drinking water.

Chlorination of protein-bound tyrosine can form 3-chlorotyrosine and 3,5-dichlorotyrosine at up to 50% molar yields (Choe et al., 2015). Bao Loan et al. demonstrated formation of 0.7–2.0 mg 3-chlorotyrosine/kg in iceberg lettuce exposed to 1.9–190 mg/L as Cl_2 and detected a median concentration of 4.5 mg 3-chlorotyrosine/kg in store-bought lettuce mixes in Belgium (Table 4) (Bao Loan et al., 2016). Similarly, Bao Loan et al. found approximately 1.4 mg 3-chlorotyrosine/kg in gilthead seabream fish treated with 95 mg/L as Cl_2 for 10 min (Bao Loan et al., 2015). Treatment of different varieties of shredded lettuce and spinach yielded total concentrations of 3-chlorotyrosine and 3,5-dichlorotyrosine of 15–60 mmol/kg (∼3.5–14 mg/kg; Table 4) (Komaki et al., 2018). Like Lee and Huang (2019), high concentrations of low molecular weight DBPs formed, including unregulated DBPs (e.g., dichloroacetamide), but their total concentrations were comparable and in some cases lower than the total concentrations of chlorotyrosines (Komaki et al., 2018) (Figure 4). Importantly, the low molecular weight DBPs partitioned to the washwater, while the chlorotyrosines remained bound within proteins in the produce. Thus, the biomolecule-based DBPs may represent a greater risk for consumer exposure, while the low molecular weight DBPs may present a greater risk for washwater disposal. CHO cell cytotoxicity assays indicated that the cytotoxicity of chlorotyrosines were greater than for the regulated THMs.

6.2. Ozone

Ozonation of bromide-containing drinking water produces BrO_3^- (von Gunten, 2003). Produce washwaters may contain bromide either from the washwater supply or by loadings of salts (i.e., total dissolved solids [TDS]) from the produce (López-Gálvez et al., 2018). Research has not evaluated the formation and uptake of BrO_3^- in ozonated produce washwaters, but given the structural similarity between ClO_3^- and BrO_3^-, some uptake of BrO_3^- may be expected.

Drinking water research has demonstrated that ozone cleaves unsaturated bonds to form aldehydes and ketones (Criegee, 1975; Frampton et al., 1999; Guzel-Seydim et al., 2004; Lagerstedt et al., 2011). Aldehydes ranging in carbon length from formaldehyde to n-tridecanal have been detected in ozonated drinking water (Richardson et al., 1999). Aldehydes are genotoxic and cytotoxic (Xie et al., 2016), particularly conjugated aldehydes (e.g., malondialdehyde) formed during oxidation of polyunsaturated fatty acids (Papastergiadis et al., 2014). Given the depletion of unsaturated

biomolecules (e.g., β-carotene, ascorbic acid) in produce upon ozonation (Alexandre et al., 2018; Alothman et al., 2010; da Silva et al., 2015; de Jesus Benevides et al., 2011; Fatima et al., 2019; Fundo et al., 2018; Jackowska et al., 2019; Karaca & Velioglu, 2014, 2020; Lombardo et al., 2015; Taiye et al., 2020; Yeoh et al., 2014), formation of aldehydes from these and other biomolecules (e.g., lipids) seems likely, but has not been evaluated. In addition to chemical transformation of biomolecules, Río Segade et al. (2017) demonstrated that treatment of grapes with gaseous ozone promoted the biogeneration of aldehydes through the lipoxygenase-hydroperoxide lyase metabolic pathway.

7. Recommendations

Despite concern over DBP formation, it is important to recognize the key role played by chemical disinfectants for controlling foodborne pathogen outbreaks in postharvest washing facilities. While there is interest in novel disinfectants (Deng et al., 2020) or disinfectant combinations, it may be difficult to identify effective disinfectants that avoid DBP formation. For example, use of UV or other photo-based disinfectants is challenging given the low transmittance of washwaters resulting from their high concentrations of dissolved COD. Moreover, UV disinfection is applied to drinking water after filtration to remove particles, thereby avoiding light shielding by the particles. Photo-based disinfection methods are expected to be poorly effective for inactivation of pathogens associated with food surfaces given the potential for pathogens located within crevices to be shielded. While chlorine and ozone are more effective for controlling pathogen cross-contamination between produce and other foods than for the inactivation of pathogens associated with food surfaces, some inactivation of surface-associated pathogens has been observed, associated with the ability of these dissolved disinfectants to diffuse into crevices. Moreover, it is important to note that drinking water research cautions against the idea that DBP-free disinfectants will be identified. For example, as a physical disinfectant, UV was thought to avoid DBP formation. However, drinking water research has found that UV disinfection can promote the formation of halogenated nitromethanes when followed by chlorination (Reckhow et al., 2010; Shah et al., 2011). While development of novel chemical disinfectants may reduce the formation of certain DBPs, drinking water research indicates that each chemical disinfectant is associated with the formation of characteristic DBPs (Shah et al., 2012). Rather than seeking a DBP-free disinfectant, research should strive to balance the clear benefits of disinfectant use for pathogen control while minimizing DBP exposure.

Most of the research to date on DBPs related to postharvest food washing facilities has focused on the same, low molecular weight DBPs of

interest to drinking water, which is not surprising given that most DBP research has focused on drinking water. While the same chemical disinfectants are used for drinking water and food processing, the conditions are very different. Low molecular weight DBPs are a concern for drinking water, because they are soluble, and even if many are volatile, they are transported to the consumer within enclosed pipelines. Moreover, there is sufficient contact time (e.g., within distribution systems) for these products to form as end products of a long series of reactions. Food processing involves short contact times in well-mixed, open tanks. Low molecular weight DBPs are likely to volatilize or remain within the washwater (Komaki et al., 2018), rather than remain within the food. Thus, the final rinsing step in postharvest washing facilities can greatly reduce exposure to many of the organic halogenated DBPs (López-Gálvez et al., 2019), although uptake of chlorate has been observed (Garrido et al., 2019). Given the very high concentrations of these DBPs in washwater relative to those in disinfected drinking waters or wastewaters, these DBPs may present a greater risk for efforts to reuse washwaters as a potable supply, particularly given that many of these DBPs readily pass through the reverse osmosis membranes employed in many potable reuse trains (Zeng et al., 2016).

Of greater concern for food consumption may be the initial intermediates formed from disinfectant reactions with biomolecules within the food. Limited research has demonstrated the transformation of protein-bound tyrosines to chlorotyrosines (Bao Loan et al., 2015, 2016; Komaki et al., 2018; Nguyen et al., 2016; Tian et al., 2020). Chlorotyrosines would be bioavailable upon liberation from proteins within the stomach. Since many other biomolecules are reactive with disinfectants, future research is needed to characterize the initial transformation products of these biomolecules to better characterize DBPs likely to affect consumer exposure. Moreover, most food-related DBP research has focused on a limited number of foods, particularly leafy greens. More research is needed on other foods, particularly meats and seafood.

The formation of these biomolecule-based, initial transformation products from reactions of chemical disinfectants with food is an unavoidable feature of the use of chemical disinfectants. Like drinking water, food processors will ultimately need to optimize disinfection systems to balance pathogen inactivation against excessive DBP formation. Switching from manual to automatic control of disinfectant dosing should facilitate striking this balance, particularly given the rapid changes in disinfectant demand associated with the leaching of COD from foods (Tudela, López-Gálvez, Allende, & Gil, 2019; Tudela, López-Gálvez, Allende, Hernández, et al., 2019). Research is needed to identify which parameters should be monitored for automatic control of processing lines. For example, monitoring

ORP may not provide sufficient resolution on chlorine residuals to ensure pathogen control (Gómez-López et al., 2014). Development of molecular markers for the presence of pathogens may expedite their detection, avoiding recalls (Gil et al., 2009). Improvements in the ability to monitor pathogen and disinfectant concentrations can help minimize disinfectant exposures to those ultimately needed for pathogen control.

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