Food Control 60 (2016) 543–551

Contents lists available at ScienceDirect

Food Control

journal homepage: www.elsevier.com/locate/foodcont

Assessment and speciation of chlorine demand in fresh-cut produce wash water

ShihChi Weng [a], Yaguang Luo [b], Jie Li [b, c], Bin Zhou [b], Joseph G. Jacangelo [a, d, e], Kellogg J. Schwab [a, e, *]

[a] JHU/MWH Alliance, 615 N. Wolfe St., Johns Hopkins University, Baltimore, MD, 21205, USA
[b] Food Quality, and Environmental Microbial and Food Safety Laboratories, U.S. Department of Agriculture, Agriculture Research Service, 10300 Baltimore Avenue, Beltsville, MD, 20705, USA
[c] College of Food Science and Technology, Huazhong Agricultural University, Wuhan, 430070, PR China
[d] MWH Global Inc., 300 North Lake Avenue, Pasadena, CA, 91101, USA
[e] Department of Environmental Health Sciences, Johns Hopkins University Bloomberg School of Public Health, 615 N. Wolfe St., Baltimore, MD, 21205, USA

ARTICLE INFO

Article history:
Received 4 June 2015
Received in revised form
20 August 2015
Accepted 25 August 2015
Available online 29 August 2015

Keywords:
Fresh-cut produce
Wash water
Chlorination
Chlorine demand

ABSTRACT

For the fresh-cut produce industry, a critical area of concern is potential pathogen cross-contamination during wash operations when wash water is reused and re-circulated in wash systems continuously imputed with fresh-cut produce. However, little research has focused on the chemical properties of wash water. Organic input from residual soil and vegetable material deteriorates water quality and creates increasing chlorine demand within this wash water.

This study evaluated the origins of chlorine demand input and chlorine decay kinetics of fresh-cut produce wash water. Using a model system, vegetable juice released per kg of processed produce for shredded romaine lettuce, shredded iceberg lettuce, shredded carrot and baby spinach was 82.1 mL/kg, 94.5 mL/kg, 158 mL/kg, and 2.26 mL/kg, respectively. Batch water analysis revealed a rapid reaction between constituents in the wash water and chlorine where over a 90 min observation period, 50% of chlorine demand occurred within first 5 min, underscoring the challenge for any water treatment process to reduce chlorine demand once vegetables are deposited into washing systems. Moreover, the results also showed sustained chlorine demand over 90-min periods, indicating an accumulative effect on chlorine consumption with continuous organic input. Additionally, HPLC-SEC analysis showed that the constituents contributing to chlorine demand are predominantly dissolved small molecules (<3400 Da), which will challenge water reuse treatment approaches. This study provides quantitative information of chlorine demand origins and chlorine decay kinetics in wash water and provides baseline data critical for integrating water reuse in the fresh produce processing industry.

1. Introduction

The demand of fresh-cut leafy green vegetables has continued to expand as consumers have integrated healthy diets with the concept of ready to eat meals. Reports by the World Health Organization (WHO, 2005) document that consumption of vegetables has benefits to human health by providing high levels of minerals and vitamins with the goal of preventing chronic diseases. Consuming uncooked food, however, has risks, such as those associated with food-borne illness outbreaks. As outlined by Center for Food Safety and Applied Nutrition, 72 outbreaks were reported to be associated with fresh produce from 1996 to 2006 with 18 out of these outbreaks due to fresh-cut produce (CFSAN, 2008). Additional outbreak investigations conducted in recent years continue to indicate that consumption of contaminated fresh-cut produce can be problematic (Barton Behravesh et al., 2011; Buchholz et al., 2011; Greene et al., 2008; Hanning, Nutt, & Ricke, 2009; MacDonald et al., 2012; Nygård et al., 2008; Söderström et al., 2008). To reduce microbial

* Corresponding author. Department of Environmental Health Sciences, Johns Hopkins University Bloomberg School of Public Health, 615 N. Wolfe St., Room E6620, Baltimore, MD, 21205 USA.
E-mail address: kschwab1@jhu.edu (K.J. Schwab).

http://dx.doi.org/10.1016/j.foodcont.2015.08.031
0956-7135/

contamination and improve produce safety, it is clear that proper sanitation is essential during fresh-cut produce postharvest processing. In the absence of a practical decontamination method to directly remove/kill pathogens from produce, washing with sanitizing water has been widely adopted by the fresh produce food industry. Although other disinfectants or disinfection methods such as ozone, organic acids, chlorine dioxide, and UV irradiation have been used (Gil, Selma, López-Gálvez, & Allende, 2009; Ölmez & Kretzschmar, 2009), addition of chlorine (or other forms of hypochlorous acid) in wash water is still the most common practice. Chlorine is predominant because of its efficacious disinfection capability against a wide spectrum of microorganisms and its economic accessibility compared to other disinfectants (Arana, Santorum, Muela, & Barcina, 1999; Baxter, Hofmann, Templeton, Brown, & Andrews, 2007; Bohrerova & Linden, 2006; Corona-Vasquez, Samuelson, Rennecker, & Mariñas, 2002; Cromeans, Kahler, & Hill, 2010; Li, Xin, Wang, Zheng, & Chao, 2002; Luh & Mariñas, 2007).

The vegetable washing process in food processing facilities is a mechanism by which water-borne pathogens can be dispersed throughout wash water. Allende, Selma, López-Gálvez, Villaescusa, and Gil (2008) reported that pathogens could carry over from previous processed produce to a subsequent batch of produce via wash water if insufficient residual chlorine is maintained in the washing tank. Luo et al. (2011) also described the importance of maintaining a minimum chlorine level during the wash process to avoid cross-contamination. However, during washing of fresh-cut produce, large amounts of organic compounds from soil debris and from exudates of produce are deposited into wash water (Luo et al., 2012). As these compounds react with chlorine, there is a rapid decrease in the level of free available chlorine as well as the potential generation of disinfection byproducts (Chen, Zhu, Zhang, Niu, & Du, 2010; López-Gálvez et al., 2010). Although chlorine replenishment is practiced during commercial produce washing operations, the level of organic compounds generated during continuous produce feeding rapidly deteriorates wash water quality in terms of depletion of chlorine and increasing turbidity and chemical oxygen demand (Luo et al., 2012). Maintaining adequate residual chlorine levels in the washing tank is challenging in commercial produce wash processes, and the resulting low chlorine level often increases the risk of cross-contamination (Luo et al., 2012).

Previous studies have predominantly focused on the association between water quality and the potential of cross contamination (Allende et al., 2008; Luo et al., 2011; Van Haute, Sampers, Holvoet, & Uyttendaele, 2013). Minimal information is available regarding quantitative assessment of the fraction of wash water responsible for observed chlorine demand, particularly in regards to organic loading. Therefore, this study evaluated the organic input per unit of processed produce during a washing process by using chemical properties (*e.g.*, chemical oxygen demand or total organic carbon) of wash water from four different vegetables (romaine lettuce, iceberg lettuce, carrots, and baby spinach). The data generated is useful in terms of estimating the quantity of chlorine demand input per mass of vegetable following different produce processing techniques. Moreover, the assessment of chlorination kinetics of these vegetable wash waters was conducted to characterize the behavior of chlorine demand in terms of reaction time and chloramine formation. By generating these data, existing and alternative industrial raw vegetable wash water processes should be able to be evaluated for the best treatment strategy. Further, use of this information could enable conceptual engineering designs for safe water reuse during leafy green washing processes.

2. Materials and methods

2.1. Vegetable wash water and vegetable extracts

Romaine lettuce (*Lactuca sativa* L.), iceberg lettuce (*L. sativa*), and carrots (*Daucus carata* L.) were purchased from a wholesale market located in Baltimore, MD. Fresh-cut samples were prepared freshly on the same day that experiments were conducted by shredding (0.32 cm in width) or chopping (6.45 cm^2) for both romaine lettuce and iceberg lettuce and shredding (0.32 cm by 0.32 cm) or slicing (0.32 cm in thickness) for carrots using a commercial food slicer (ECD-302; Nichimo International Inc., WA). Freshly harvested baby spinach leaves were received from Taylor Farms (Jessup, MD) and were processed without cutting.

Washing experiments were conducted by submerging prepared produce in a washing tank containing sterile deionized water at a produce:water ratio of 1 kg:20 L for prepared romaine lettuce, iceberg lettuce, and baby spinach samples and a ratio of 1 kg:40 L for prepared carrot samples at room temperature (22 °C). During each simulated wash cycle, 1 kg of prepared produce sample was packed in a mesh bag and completely submerged into washing tank for 1 min. The romaine lettuce, iceberg lettuce, and baby spinach were processed for a total of 15 simulated wash cycles and the carrots for 10 simulated wash cycles. A new batch of prepared produce was used for each simulated wash cycle and additional fresh water was added as needed to maintain a fixed volume between simulated wash cycles, which simulated the continuous operation in a commercial setting. Thus, a batch of 15 kg of produce was used in total during washing experiments for romaine lettuce, iceberg lettuce, and baby spinach and 10 kg in total during washing experiments for carrots. Samples were collected at the end of experiment or as needed between simulated wash cycles.

Vegetable liquid exacts of all four vegetables were prepared following the method of Shen et al. (2012) with a commercial household juice maker (Breville Model BJE200XL Juice Fountain, Shanghai, China). The liquid portion was collected, filtered with cheesecloth to remove coarse vegetable fragments and stored at −20 °C until use.

2.2. Analytical methods

Samples from washing experiments and from vegetable extracts were prepared with a proper dilution ratio to fit the detection range of analytical methods. The analysis included chemical oxygen demand (COD) by colorimetric method (method 5220; APHA-AWWA-WEF (2012)) using the TNT 822 COD Kit (Hach Company, CO), nitrogen composition analysis by colorimetric method using TNT 880 simplified TKN kit (Hach Company, CO), total organic carbon (TOC) by persulfate-ultraviolet oxidation method (Method 5310; APHA-AWWA-WEF (2012)) using a Sievers 900 series TOC analyzer (GE Analytical Instrument, CO), ultraviolet light absorbance at wavelength of 254 nm (UV_{254} abs.) using a DR4000U spectrophotometer (Hach Company, CO), and anions analysis by IC25 ion chromatography system with IonPac© A17 column (Thermo Scientific, CA).

2.3. Chlorination experiments

The final wash water samples were collected from washing experiments using four vegetable types as described above and were subjected to chlorination where 1 mL of sample was mixed with 0.02 mL of diluted chlorine stock solution (80,000–8000 mg/L as Cl_2) in form of sodium hypochlorous acid (NaOCl, 10–15%, Sigma–Aldrich). The applied chlorine concentration varies from 1600 to 160 mg/L as Cl_2 based on the chlorine demand in various wash waters and the feasibility for analysis by selected methods. Time-