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Immersion-free, single-pass, commercial fresh-cut produce washing system: An alternative to flume processing

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ABSTRACT

Fresh-cut vegetable processing in the USA typically involves submerging produce in chlorinated water that is often reused and re-circulated. However, this washing practice is water and chemical intensive and subject to rapid decreases in free chlorine concentration, which may increase the probability of water mediated microbial cross-contamination. An immersion-free, single-pass produce washing system was recently developed to address these challenges by over-head spraying clean (retreated) water, rather than spent wash water. The objective of this study was to compare single-pass and flume systems during commercial processing of fresh-cut vegetables in terms of wash water physicochemical and microbiological quality and cut produce microbiological and sensorial quality. Two products, shredded iceberg lettuce and diced cabbage, were selected; processes were evaluated for each product on three separate days. Wash water and produce were sampled every 30 min during production for 2.7 h. Water that was used to wash the produce was collected from representative locations in the single-pass (input water, pre-wash, cutter, incline wash, vibra-wash) and flume (flume A, flume A catch tank, flume B, flume B catch tank) systems. Physicochemical (free chlorine, total chlorine, pH, total dissolved solids (TDS), chemical oxygen demand (COD), turbidity) and microbial analyses (aerobic plate count (APC)) were conducted on the wash water samples. Produce samples collected after cutting and after washing were analyzed onsite for APC immediately after collection. Final packaged products were analyzed weekly for sensorial quality (visual, olfactory, overall acceptability) during three weeks of storage at 1 °C by a trained panel using a 9-point hedonic scale. Results show that the organic load indicators in wash water samples from the single-pass system were consistent over time for most sampling locations, with no statistically significant increases in turbidity, TDS, or COD during production. In contrast, the organic load indicators in wash water samples from the flume system increased significantly during production by 13–45 NTU h^{-1} for turbidity, 382–1094 mg L^{-1} h^{-1} for TDS, and 597–2772 mg L^{-1} h^{-1} for COD. For the single-pass system, the wash water from the cutter had the largest APC of 3.8–4.2 log CFU/100 mL and the highest values of organic load indicators (152–186 NTU for turbidity, 623–904 mg L^{-1} for TDS, and 4420–4673 mg L^{-1} for COD) compared to the wash water from all the other processing stages (input water, pre-wash, incline, vibra-wash), which ranged from $<$ 0.6–2.4 log CFU/100 mL for APC, 0.3–97 NTU for turbidity, 245–471 mg L^{-1} for TDS, and 62–1942 mg L^{-1} for COD. There were no significant differences ($p > 0.05$) in APC between the single-pass and flume washed product samples; APC on the final product samples ranged from 3.2 to 3.4 log CFU g^{-1} for lettuce and 3.9–4.1 log CFU g^{-1} for cabbage. Panelists rated the quality of the products washed using the single-pass system as comparable to those washed using the flume system within the first two weeks and slightly better after three weeks of storage. Results from this study could be used by the produce industry to further optimize the single-pass system and develop additional processing innovations to improve the safety, efficacy, economics, and environmental impacts of produce washing systems.

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1. Introduction

Immersion-based fresh-cut produce washing in chlorinated water has been widely used in the United States, since the inception of the fresh-cut produce industry. However, this process generally requires substantial water and chemical use (Manzocco et al., 2015; Castro-Ibanez et al., 2017). A typical immersion-based process for fresh-cut produce includes cutting, a sequential double flume wash using chlorinated water, water removal, and packaging (Maffei et al., 2016; Gil et al., 2015; Artés et al., 2009). At the start of a typical flume washing operation in the USA, fresh, potable water is mixed with chlorine in the form of sodium hypochlorite and the pH is adjusted using an acidulant. Economic and environmental considerations make it necessary to reuse spent wash water during production (Manzocco et al., 2015). Many batches of cut produce (thousands of kilograms) are washed in these same tanks of water during each shift; a small amount of fresh chlorinated water is periodically added back to the tanks to maintain a constant volume. This practice results in the accumulation of organic matter in the wash water, including dirt and produce exudate from the cut tissue, which readily neutralizes free chlorine (Gil et al., 2009; Gombas et al., 2017; Holvoet et al., 2012; Gòmez-López et al., 2013; Allende et al., 2008). For this reason, chlorine must be added to the flume water regularly in order to maintain the sanitizer efficacy and prevent the survival of microorganisms in the wash water. The rapid consumption of free chlorine in the presence of a high organic load makes maintaining a stable, free chlorine level challenging; it also increases the probability that a food safety hazard will occur, as failure to maintain a minimal free chlorine level may provide opportunities for the survival and spread of foodborne pathogens (Gombas et al., 2017; Luo et al., 2011; Murray et al., 2018).

Commercially available control systems can maintain a desired free chlorine level during industrial produce washing in flume systems for some products, such as chopped lettuce or baby spinach. However, these control systems may not be as effective in maintaining a stable free chlorine level for other types of products with higher organic loads, such as shredded carrot, chopped onion, and diced cabbage. Due to the challenge of maintaining a stable free chlorine level in the wash water, there could be an increased probability of microbial cross-contamination over time, as more product is washed in the same water. Additional challenges of using flume systems include a decline in wash water quality over time and a build-up of chlorination disinfection by-products in the wash water (Gil et al., 2015; Luo et al., 2018).

To address these challenges, McEntire et al. (2016) developed and patented a single-pass commercial system that uses retreated, spent wash water (solids and organics removed to produce clean, fresh water) in a series of over-head sprayers. This newly developed immersion-free washing system sprays chlorinated water onto fresh-cut produce in a single-pass, avoiding the recirculation of spent wash water with its accumulated organic load. While the system is referred to as single-pass because the water is not recirculated, the produce is sprayed multiple times as it is conveyed along a belt under a series of overhead spray bars. The system is also designed to tumble the produce so both sides are exposed to the chlorinated wash water. The spent wash water is collected at an onsite water treatment facility and the reclaimed water is reused to wash produce. By using clean chlorinated wash water in a single-pass approach, a higher concentration of sanitizer can be more easily maintained while decreasing the total chemical consumption compared to traditional fresh-cut washing methods (McEntire et al., 2016). The single-pass system includes an optional pre-wash of the whole heads of produce (e.g., lettuce or cabbage), cutting, spraying water on the product using an inclined belt and a series of vibrating screens, water removal, and packaging (McEntire et al., 2016).

Several studies conducted in commercial fresh-cut produce operations have published results focused on the characteristics and dynamic changes in flume washing systems (Barrera et al., 2012; Luo et al., 2018; Murray et al., 2018; Holvoet et al., 2012; Maffei et al., 2016; Allende et al., 2004; Meireles et al., 2017; Salomonsson et al., 2014). The recently developed single-pass system has not been characterized previously nor has it been compared to a flume system. Therefore, the objective of this study was to compare single-pass and flume systems during commercial processing of fresh-cut lettuce and cabbage. Specifically, we aimed to compare the wash water physicochemical and microbiological quality, and the cut produce microbiological and sensorial quality between the two systems.

2. Materials and methods

2.1. Fresh-cut processing plant operation

This study was conducted during the regular commercial operation of a medium-size fresh-cut produce processor in the USA; this unique processing plant used both single-pass and flume washing systems for fresh-cut produce processing. Field-cored iceberg lettuce (*Lactuca sativa* var. *capitata*) and whole cabbage (*Brassica oleracea* var. *capitata*) were stored for less than two days at 5 °C before processing.

Iceberg lettuce was sliced into 6 mm strips using a TranSlicer® 2510 Cutter (Urschel Laboratories Inc., Chesterton, IN, USA). Cabbage, after onsite coring, was diced into 6 mm squares using a Diversa Cutter (Urschel Laboratories Inc.) with water injection. The cut vegetable pieces were immediately washed using either the single-pass or the flume system (described in Section 2.2) with a targeted residence time of 30 s. Input water was pre-chilled to 4 °C, chlorinated with sodium hypochlorite, and pH adjusted with a phosphoric acid-based acidulant (Lemons, 2016; Luo et al., 2012). The temperature of the processing facility was approximately 4 °C. The processing throughput was approximately 20 and 30 kg min^{-1} in the single-pass system and 30 and 50 kg min^{-1} in the flume system for iceberg lettuce and cabbage, respectively. After washing in chlorinated water and rinsing in potable water, the same centrifugal water removal and packaging methods were employed for products from both washing processes.

2.2. Vegetable washing systems

The single-pass system (McEntire et al., 2016) consisted of a series of over-head sprayer manifolds installed over a pre-cutter incline belt (pre-wash), post-cutter incline belt (incline wash), and a cascade of vibrating screens (vibra-wash) designed to tumble the cut product (Fig. 1A). Chlorinated, pH adjusted potable water chilled to 4 °C was used in this single-pass, non-recirculated spraying system. The spent wash water was collected at an ancillary water treatment facility, reclaimed (treated to generate potable water), and re-used in the single-pass system to conserve and improve water usage efficiency. The water treatment facility (approximately 750 L min^{-1} capacity) was equipped with conventional coagulation, flocculation, and sedimentation treatments, as well as advanced ultrafiltration, reverse osmosis, and ultraviolet treatments (AVANTech, Inc., Columbia, SC, USA). After conventional and advanced treatments, the water was chlorinated and blended with city potable water or well water. This blended water was transferred to a batch tank connected to the single-pass system; the final water chlorination was controlled in the batch tank using an automated pH and free chlorine feedback system (Automated Analytic Platform™, Smart Wash Solutions Inc, Salinas, CA, USA).

The flume system consisted of a primary flume (9000 L, flume A) and a secondary flume (7000 L, flume B) (Luo et al., 2018). A de-watering shaker with a 1 mm screen at the end of each flume allowed the spent wash water to be collected into catch tanks, both primary (catch tank A) and secondary (catch tank B), where it was reconditioned (fresh water added, chlorine replenished, pH controlled) and recirculated back into the respective flumes (Fig. 1B). A portion of the recirculated wash water was chilled to 4 °C and the water from flumes A and B was kept in separate lines inside the chiller and were not mixed. Wash water chlorination in each flume was controlled using automated pH and free

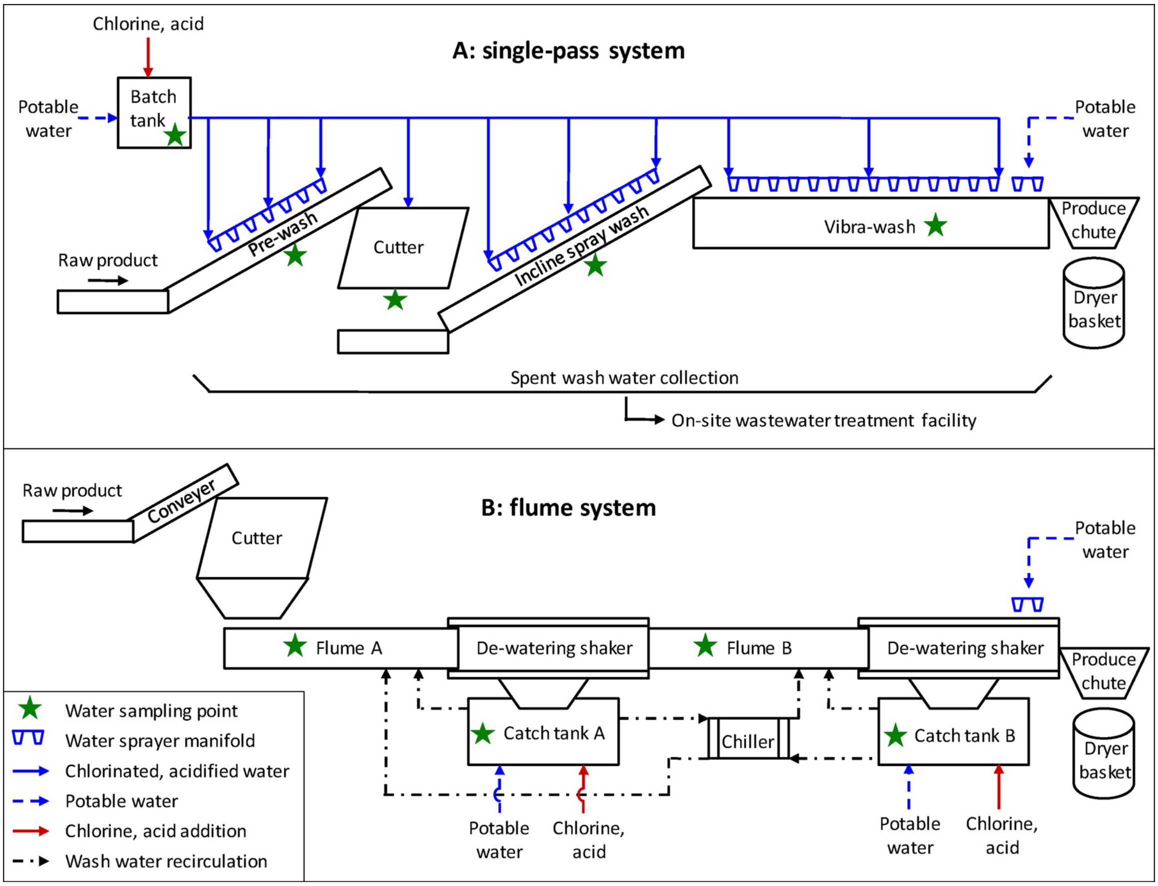

Fig. 1. Diagram of commercial fresh-cut produce washing processes, including a single-pass system (A) and flume system (B, modified from Luo et al., 2018). Water sampling points utilized during this study are also shown. In the flume system, wash water that was recirculated from flume A and B were kept in separate lines and did not mix in the chiller.

chlorine feedback systems (described above).

2.3. Water and produce sample collection

On the same day, iceberg lettuce or cabbage from matching lots was processed in both the single-pass and flume washing systems. Samples were collected during three production runs conducted on three separate days for each product. Wash water and produce samples from each production line were taken beginning 10 min after the start of production to allow the line throughput to stabilize, and every 30 min thereafter for 2.7 h of operation, when the line closed. The input water to the single-pass line was sampled after 10, 70, and 130 min of processing.

Wash water samples (~200 mL) were collected with a sterile disposable beaker from five locations in the single-pass system: input water, pre-wash, cutter, incline wash, and vibra-wash (Fig. 1A), and four locations in the flume system: flume A, catch tank A, flume B, and catch tank B (Fig. 1B). Physicochemical and microbiological analyses of the water samples were performed on-site, immediately.

Produce samples for microbiological analysis were collected from one location in the single-pass system: after packaging (final product), and two locations in the flume system: after cutting (before washing) and after packaging (final product). Both single-pass and flume systems used the same cutter and cutting process, and the unwashed cut products from both systems were assumed to be equivalent. Therefore, produce samples were not taken after cutting (before washing) from the single-pass system. Produce samples for microbial analysis were processed on-site immediately after collection and the excess water was removed from the samples using a salad spinner.

Packaged (final) products for quality evaluation were collected by the processor's quality assurance personnel and shipped in refrigerated trucks (2–4 °C) to a distribution center in Virginia (approximately 7 h in transit), where it was transferred to coolers containing frozen cold packs in a van and driven an hour to the Food Quality Laboratory at the Beltsville Agricultural Research Center (BARC) in Beltsville, MD, USA for quality and shelf-life evaluation.

2.4. Physicochemical analysis

Physicochemical analyses performed on the water samples included free chlorine, total chlorine, pH, turbidity, total dissolved solids, and chemical oxygen demand. Free and total chlorine and pH were measured immediately after the sample was collected, while all other parameters were measured within 4 h of sample collection (samples were stored at 4 °C). The concentration of free chlorine (FC) and total chlorine (TC) was measured with a chlorine photometer using the N,*N*-diethyl-p-phenylenediamine (DPD) method (CP-15, HF Scientific Inc., Fort Myers, FL, USA). pH was measured using a calibrated pH meter (Oakton Instruments, Vernon Hills, IL, USA) and turbidity was measured using a calibrated turbidimeter (Orion AQ4500, Thermo Scientific, Singapore). The concentration of total dissolved solids (TDS) was measured using a TDS meter (135 A, Thermo Orion, Germany). Chemical oxygen demand (COD) was quantified by a mercury-free reactor digestion method (Method 10236, Hach Company, Loveland, CO, USA).

2.5. Microbiological analysis

Aerobic mesophilic bacteria in wash water samples and on produce samples were enumerated immediately after collection using aerobic plate count (APC) petrifilm plates (3 M Microbiology, Maplewood, MN, USA). Each wash water sample was filtered through a 0.3 mm polyethylene filter (Nasco, Fort Atkinson, WI, USA) and 100 mL was transferred to a sterile bottle that was pre-filled with sodium thiosulfate (100 mg) for chlorine neutralization. A 1.0 mL aliquot of each wash water sample was plated in duplicate on APC petrifilm plates and a portion of each water sample was also enriched in triplicate by combining 10 mL of sample with 2 mL of 5× tryptic soy broth (Becton, Dickinson and Company, Franklin Lakes, NJ, USA). The APC petrifilm plates and enriched wash water samples were incubated at 35 °C for 36 h. After incubation, the colonies on the APC petrifilm plates were enumerated using a petrifilm plate reader (3 M Microbiology, Maplewood, MN, USA). If no counts were obtained from the APC petrifilm plates, 100 µL of each enriched water sample was streaked onto tryptic soy agar to confirm that there was bacterial growth. The bacterial counts in the wash water were estimated based on the number of tubes that were positive for bacterial growth (3 tubes, 1 dilution) using a most probable number (MPN) calculator (Curiale, 2004). The limit of detection for the water samples was 50 CFU/100 mL using the petrifilm plates, which was improved to 4 MPN/100 mL using this 3-tube enrichment estimation.

Produce samples (25 g) were macerated for 2 min with 125 mL of sterile phosphate buffered saline in a stomacher bag (750 mL) (Nasco) using a stomacher (Stomacher® 400 Circulator, Seward Ltd., Worthing, UK), followed by filtration, as described above. Serial 10-fold dilutions were performed for produce rinsate samples, as necessary. Each sample (1 mL) was plated in duplicate on APC petrifilm plates, followed by incubation at 35 °C for 36 h, and colony enumeration using a petrifilm plate reader. The limit of detection was 3 CFU g^{-1} for the produce samples.

2.6. Quality and shelf life evaluation

Upon arrival at the BARC Food Quality Laboratory for quality and shelf-life assessments, finished fresh-cut products (2.3 kg bags) were stored at 1 °C for up to three weeks, with weekly quality evaluations. These storage conditions were selected based on commercial practices and previous studies on fresh produce (Ahvenainen, 1996; Kim et al., 2005a). For each weekly assessment, six bags of each product, from each of the three processing days (36 bags total) were evaluated. Due to unforeseen logistical challenges, there was a shipment delay of lettuce from two of the processing days and cabbage from one of the processing days; this resulted in some of the samples missing the week-one quality evaluation. The week-one quality evaluation included only one processing day (six bags) for lettuce and two processing days (12 bags) for cabbage.

Produce quality evaluation was conducted by a trained panel of volunteers from BARC (5–6 members). The panelists (4 males and 1–2 females) were instructed on sensory evaluation techniques for assessing the visual, olfactory, and overall acceptability of fresh-cut lettuce and cabbage. Panelists were trained to recognize differences in the intensity of each attribute for both products using example lettuce and cabbage samples. Visual acceptability was rated based on the appearance of the entire sample, where negative product attributes included limp/wilted, decayed, discolored, or damaged pieces. Olfactory acceptability was rated based on the product smell and the presence of off-odor. Panelists sniffed coffee beans to cleanse their nose in-between samples (McDonald et al., 2016). Panelists rated each attribute on a 9-point hedonic scale, including 'like extremely' (9), 'like very much' (8), 'like moderately' (7), 'like slightly' (6), 'neither like nor dislike' (5), 'dislike slightly' (4), 'dislike moderately' (3), 'dislike very much' (2), or 'dislike extremely' (1) (Meilgaard et al., 1999; Allende et al., 2003; Medina et al., 2012; Tudela et al., 2013). The panel was informed that an acceptable or marketable rating was greater than or equal to (6) 'like slightly'.

During each evaluation session, six samples of either lettuce or cabbage were randomly presented to the panelists on white trays labeled with random 3-digit codes; all six samples were placed on a white rectangular tray. Each panelist evaluated one sample from each bag of product stored for 1–3 weeks. A total of 15 unique evaluation sessions were conducted to assess the quality of the all the products.

2.7. Statistics

Statistical analysis was conducted using PROC MIXED, SAS v9 (SAS Institute Inc., Cary, NJ, USA). Sensory data were analyzed using Analysis of Variance (ANOVA), with storage times and panelists as random effects. All other data sets were analyzed using Analysis of Covariance (ANCOVA), specifying sampling time as a continuous-valued regressor (i.e., covariate) to model any linear drift during the washing process. Significant linear drift was defined by a non-zero ($p < 0.05$) linear time coefficient from the ANCOVA, together with a moderate (0.5–0.7) or strong (> 0.7) Pearson correlation coefficient (PCC). When the linear drifts were not significant or were consistent across processes or locations within a process, comparisons were made by combining data from all sampling times. Pairwise means comparisons among locations within a washing process were conducted using the PDMIX800.SAS macro (Saxton, 1998) and specifying ADJUST = SIDAK to maintain experiment-wise $\alpha = 0.05$.

Correlations among measurements recorded throughout each washing process were modeled using various covariance structures. Covariance structures were needed to model the data because there were correlations between the variables (measurements were not independent of one another) and the data sets had unequal variances. The covariance structure appropriate for a specific model was chosen using the AICC goodness of fit statistic, to ensure it accurately modeled the observed variability. Specifically, a first-order auto-regressive covariance structure was used to model the APC of the produce and COD in the wash water. A compound symmetric covariance structure was used to model the turbidity. A Kronecker product of unstructured x compound symmetric covariance structure was used to model the APC, TDS, and pH of the wash water. A Kronecker product of unstructured x first-order autoregressive covariance structure was used to model the free chlorine and total chlorine in the wash water.

3. Results

3.1. Physicochemical properties of wash water

Wash water physicochemical parameters (FC, TC, pH, turbidity, TDS, COD) were plotted against processing time (see supplemental data) and analyzed for linear trends with time. The single-pass system wash water showed no significant increases in turbidity, TDS, COD, or TC during processing, except for the cabbage incline wash water turbidity (linear slope 35 ± 8 NTU h^{-1}) and COD (linear slope 936 ± 337 mg L^{-1} h^{-1}). For most sampling locations in the flume system, the wash water turbidity, TDS, and COD for both lettuce and cabbage had significant linear trends with positive slopes (Table 1), indicating accumulation of organic materials. Previous studies (Luo, 2007; Luo et al., 2018) have also shown that turbidity, TDS, and COD increased in a similar pattern to that of organic materials in produce wash water. The pH and FC of the wash water from all single-pass and flume sampling locations did not exhibit significant linear relationships with time, except for the lettuce input wash water pH (linear slope −0.3 ± 0.1 h^{-1}) and the cabbage incline wash water free chlorine (linear slope -8 ± 2 mg L^{-1} h^{-1}).

Wash water organic load indicators (turbidity, TDS, COD) were averaged across all sampling times in the single-pass and flume systems

Table 1
Analysis of covariance (ANCOVA) linear regression model results for the slope of the flume wash water total chlorine (TC), turbidity, total dissolved solids (TDS), and chemical oxygen demand (COD) over time. Only slopes from locations with significant linear relationships ($p < 0.05$, Pearson correlation coefficient > 0.5) are shown. The slopes were determined using all the data collected during 2.7 h of production.

Product	Location	TC ($mg\ L^{-1}\ h^{-1}$)*	Turbidity ($NTU\ h^{-1}$)*	TDS ($mg\ L^{-1}\ h^{-1}$)*	COD ($mg\ L^{-1}\ h^{-1}$)
Lettuce	Flume A	9.8	22.6	686	737
	Catch tank A	9.2	19.3	690	827
	Flume B	–	14.8	476	649
	Catch tank B	–	13.4	382	597
Cabbage	Flume A	6.8	44.7	1094	2772
	Catch tank A	6.2	44.0	1048	2714
	Flume B	7.2	18.8	739	1790
	Catch tank B	8.4	19.2	740	1478

*Estimated standard error from the ANCOVA was ± 2.6 for TC, ± 6.5 for turbidity, ± 95 for TDS, and ± 312 for COD.

(Fig. 2). In the single-pass system, the organic load in the spent wash water was greatest from the cutter, followed by the incline and vibra-wash, and pre-wash for both lettuce and cabbage. For lettuce washing in the flume system, TDS was significantly greater ($p < 0.05$) in flume A and catch tank A than in flume B and catch tank B, but there were no significant differences in wash water turbidity and COD between the primary and secondary flumes. The organic load in the flume system was significantly greater ($p < 0.05$) in flume A and catch tank A compared to flume B and catch tank B during cabbage washing, as indicated by turbidity, TDS, and COD.

In addition to the parameters discussed above, the average pH, FC, and TC across all sampling times in the single-pass and flume systems were also determined (Table 2). In the single-pass system for both lettuce and cabbage, there were significant differences in the spent wash water pH, FC, and TC, among the sampling locations. In the input wash water, the FC:TC ratio was close to 1.0, indicating that chlorine was present almost exclusively in the form of FC. For the flume system, there were no statistically significant differences ($p > 0.05$) in wash water pH, FC, or TC among sampling locations, except for TC in the cabbage wash water, which was significantly greater in flume A and catch tank A than in flume B and catch tank B. All the spent wash water samples from both single-pass and flume systems had TC averages that were greater than FC, indicating that chlorination disinfection by-products had accumulated in varying amounts in the spent wash water.

3.2. Microbial survival in wash water

The APC of the lettuce and cabbage wash water samples from the single-pass and flume systems was averaged across all sampling times (Table 3). There were no significant linear trends in APC of the wash water during processing from either system, except for the cabbage wash water from the cutter, with a linear slope of -1.0 ± 0.1 log MPN/100 mL/h (see supplemental data). In the single-pass system, there were significant differences in APC between sampling locations, with the cutter wash water having a greater APC (3.8–4.2 log CFU/100 mL) than all other locations, which ranged from < 0.6 to 2.4 log CFU/100 mL. For both lettuce and cabbage, there were no significant differences in the flume wash water APC between sampling locations, with values ranging from 0.7 to 1.3 log CFU/100 mL.

3.3. Microbial population on produce

There were no significant linear trends in APC from the produce during processing, except for the cabbage from the single-pass system, with a linear slope of -0.5 ± 0.1 log CFU $g^{-1}\ h^{-1}$ (see supplemental data). Average APC during production was employed to compare the microbial populations on cut produce before washing and final products after washing with the single-pass and flume systems (Fig. 3). There were no significant differences in APC between the single-pass and flume washed lettuce or cabbage; in other words, both washing systems were equally effective at reducing aerobic mesophilic bacterial population from the produce surfaces. For lettuce samples, APC was consistently lower for both the single-pass and flume washing processes than for the cutter samples; washing reduced the APC from the lettuce by approximately 1.0 log g^{-1}. For cabbage samples, there were no significant differences in APC; washing did not reduce the aerobic mesophilic bacterial population on cabbage.

3.4. Sensory evaluation of produce

Acceptability ratings of visual, olfactory, and overall sensory attributes were determined weekly for single-pass and flume washed lettuce (Fig. 4I, III, V) and cabbage (Fig. 4II, IV, VI) stored at 1 °C for up to three weeks. Overall, panelists rated the products washed using the single-pass system as good as, or better than flume washed products throughout the storage time. As the storage time increased, so did the differences between the quality ratings of products from these two processes. Both products maintained high quality ratings throughout the first two weeks of storage, with average sensory ratings between 8 (like very much) and 9 (like extremely).

There were no significant differences in sensory attribute ratings between the single-pass and flume washed lettuce or cabbage after one week; average attribute ratings ranged from 8.3 to 9.0 for lettuce samples and 8.7–8.9 for cabbage samples. After two weeks of storage, products from the single-pass system rated slighlty better than the flume system for the lettuce visual acceptability and cabbage olfactory acceptability, with lettuce visual ratings of 8.2 ± 0.2 (single-pass) and 7.9 ± 0.2 (flume), and cabbage olfactory ratings of 8.4 ± 0.2 (single-pass) and 8.1 ± 0.2 (flume).

After three weeks of storage, all three sensory attributes for lettuce and cabbage from both single-pass and flume systems had significantly deteriorated (lower ratings) compared to the ratings after one or two weeks of storage, which were not significantly different from each other. The quality deterioration after three weeks of storage was more pronounced for products washed in the flume system compared to the single-pass system. Products from the single-pass system rated significantly better than the flume system for all attributes (overall, olfactory, visual acceptability) after three weeks of storage, with average ratings between 6.8–8.0 (single-pass) and 6.0–7.5 (flume) for lettuce samples and 5.9–7.6 (single-pass) and 4.9–7.2 (flume) for cabbage samples.

4. Discussion

In this study, a new single-pass spray wash system was compared with a flume wash system in the same commercial plant processing shredded iceberg lettuce and diced cabbage. The physicochemical parameters (turbidity, TDS, COD, TC) of the wash water samples from the single-pass system did not increase significantly during production, except for the cabbage incline wash water turbidity and COD. In

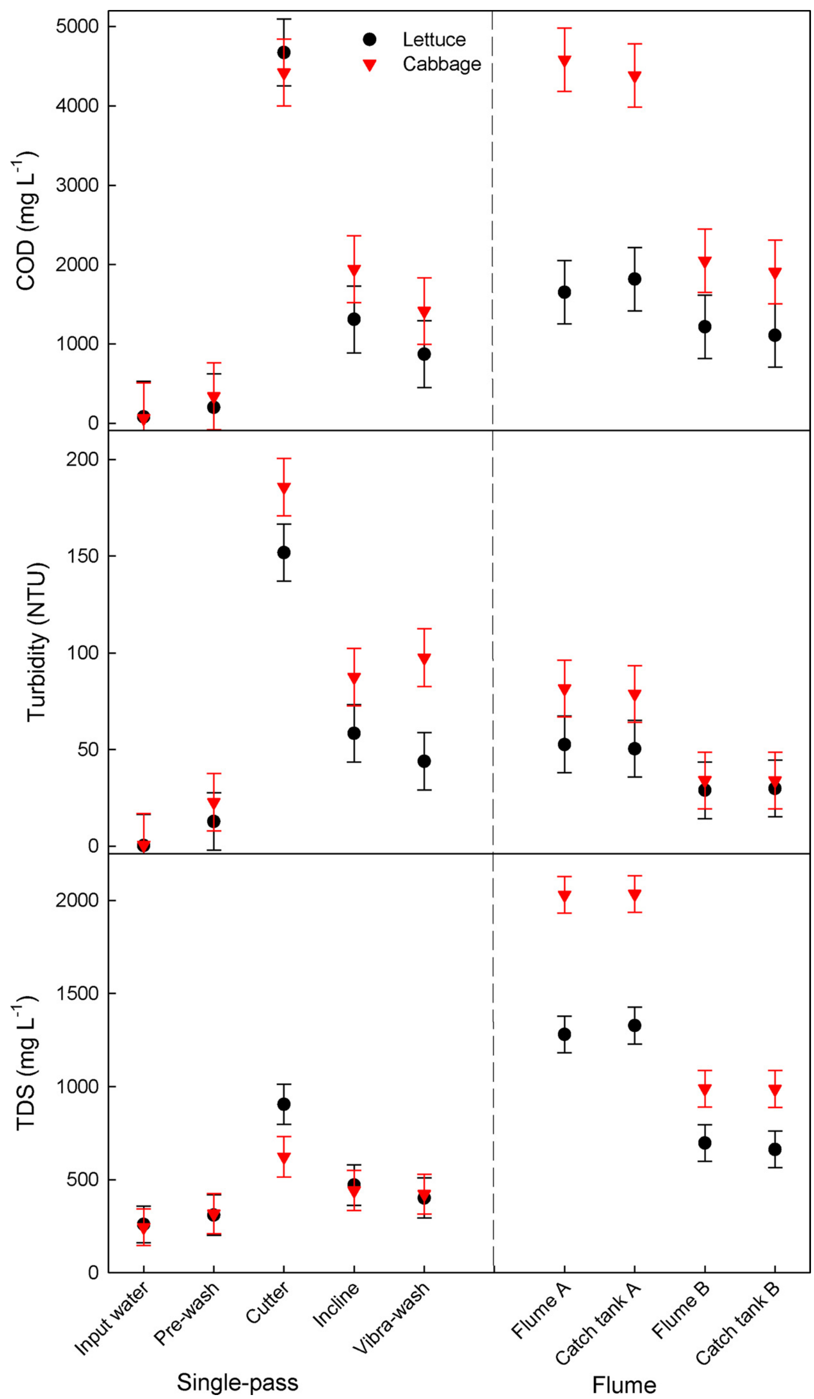

Fig. 2. Chemical oxygen demand (COD), turbidity, and total dissolved solids (TDS) of wash water samples were averaged across all time points during 2.7 h of production with estimated standard error. Flume system data from Luo et al. (2018) are shown for comparison to the single-pass system.

contrast, the organic load in the flume wash water increased over time, as judged by turbidity, TDS, and COD. The flume results matched expectations based on previous studies that showed an increasing organic load in flume systems with reused water (Zhou et al., 2014; Luo et al., 2012). During production, the wash water quality from the single-pass system was more consistent and better controlled than in the flume system. The TC in the flume wash water increased over time while the FC fluctuations did not have a consistent trend with time, which implies there was an accumulation of chlorination disinfection by-products; this agrees with findings from Murray et al. (2018). In both systems, the wash water had an acidic pH, ranging from 3.8 to 5.5; even with these low pH values, a minimal amount of chlorine off-gassing was observed because the patented phosphoric acid based process aid used to control pH also stabilized chlorine (Lemons, 2016; Luo et al., 2012).

The increasing turbidity and COD of the cabbage incline wash water over time indicates that process modifications may be necessary to reduce the organic load or allow better drainage of the incline wash water during cabbage processing. For example, the water flow rate through each spray nozzle could be increased to help reduce the organic load of the cut product in the incline or cutter sections. Additionally, the conveyor belt could be modified to decrease the amount of small cabbage pieces that become stuck in the holes of the conveyor belt. Despite the increases in organic load for cabbage wash water from the incline, overall, the single-pass wash system seemed to be beneficial in

Table 2
Average pH, free chlorine (FC), and total chlorine (TC) of wash water samples across all time points.

Process	Location	pH*		FC (mg L^{-1})*		TC (mg L^{-1})*	
		Lettuce	Cabbage	Lettuce	Cabbage	Lettuce	Cabbage
Single pass	Input water	5.2^{a}	5.1^{a}	65^{a}	64^{a}	67^{a}	64^{a}
	Pre-wash	4.4^{b}	4.4^{bc}	44^{b}	34^{b}	51^{b}	39^{b}
	Cutter	4.6^{b}	4.8^{ab}	2^{c}	2^{c}	32^{c}	25^{c}
	Incline	3.8^{c}	4.3^{cd}	6^{c}	8^{c}	24^{c}	24^{c}
	Vibra-wash	3.8^{c}	4.1^{d}	14^{c}	10^{c}	26^{c}	27^{c}
Flume	Flume A	5.2^{A}	5.3^{A}	17^{A}	33^{A}	37^{A}	60^{A}
	Catch tank A	5.3^{A}	5.4^{A}	18^{A}	36^{A}	37^{A}	61^{A}
	Flume B	5.5^{A}	5.5^{A}	9^{A}	11^{A}	17^{A}	20^{B}
	Catch tank B	5.4^{A}	5.3^{A}	10^{A}	10^{A}	18^{A}	22^{B}

Lowercase letters show significant differences ($p < 0.05$) between sampling locations in the single-pass system for each produce type (lettuce or cabbage). Uppercase letters show significant differences ($p < 0.05$) between sampling locations in the flume system for each produce type. Flume system data from Luo et al. (2018) are shown for comparison to the single-pass system.
*Estimated standard error from the ANOVA was ± 0.1 for flume and single-pass pH (except the input water, which was ± 0.2), ± 18 for flume FC, ± 9 for flume TC, and ± 4 for single-pass FC and TC.

Table 3
Average aerobic plate count (log MPN/100 mL) of wash water samples across all time points.

Process	Location	Lettuce*	Cabbage*
Single pass	Input water	< 0.6**	< 0.6**
	Pre-wash	0.7^{c}	0.7^{b}
	Cutter	4.2^{a}	3.8^{a}
	Incline	2.4^{b}	1.3^{b}
	Vibra-wash	1.7^{b}	1.1^{b}
Flume	Flume A	1.1^{A}	0.8^{A}
	Catch tank A	1.3^{A}	0.8^{A}
	Flume B	0.8^{A}	0.8^{A}
	Catch tank B	0.7^{A}	0.7^{A}

Lowercase letters show significant differences ($p < 0.05$) between sampling locations in the single-pass system for each produce type (lettuce or cabbage). Uppercase letters show significant differences ($p < 0.05$) between sampling locations in the flume system for each produce type. Flume system data from Luo et al. (2018) are shown for comparison to the single-pass system.
*Estimated standard error from the ANOVA was ± 0.3 for all locations.
**Less than the limit of detection, 0.6 log MPN/100 mL.

preventing organic load build-up during production by not recirculating spent wash water.

During this study, the flume system throughput (30–50 kg min^{-1}) was higher than that of the single-pass system (20–30 kg min^{-1}). However, these values did not match typical throughput amounts, according to the produce processor. This discrepancy in the line throughput could be attributed to the plant workers paying additional attention to detail and adding steps to ensure test accuracy, and short total production time (2.7 h) of the trial. During the research study at the manufacturing plant, we also observed that the change-over time was generally much faster for the single-pass system than the flume system. A significant amount of time was required to drain and clean the large tanks of water in flume system, and after refilling the tanks with clean water for the next production run, additional time was needed to adjust the water chlorine and pH levels; none of these time-consuming steps were needed in the single-pass system. Given the difference in throughput and testing limitations commonly encountered during commercial trials, additional tests at the pilot-scale with precisely controlled conditions are warranted.

Although most wash water samples had no significant linear trends in APC over time, there were variations among sampling locations in the single-pass system. Wash water from the cutter in the single-pass system had a significantly greater surviving population of aerobic mesophilic bacteria and had the highest organic load indicators (turbidity, TDS, COD). This implies that the cutter could be a critical processing step at which an intervention could help prevent cross contamination.

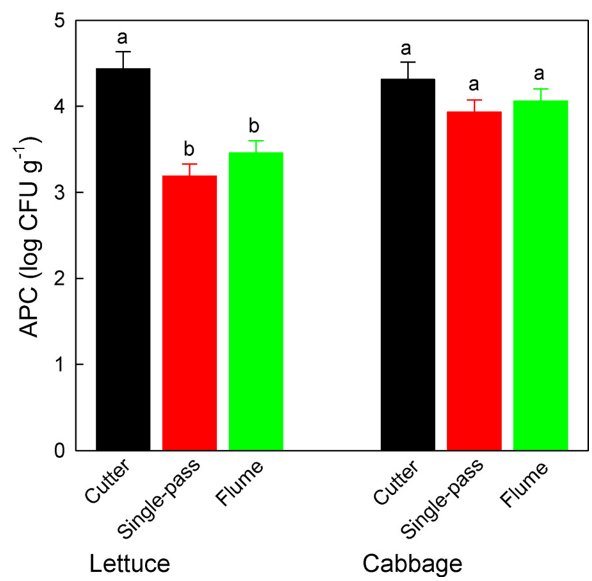

Fig. 3. Average aerobic plate count (APC) with estimated standard error for shredded lettuce and diced cabbage samples that were taken from after the cutter and after washing in the single-pass or flume systems during 2.7 h of production. Letters show significant differences between sampling locations within each produce type ($p < 0.05$). The limit of detection was 0.5 log CFU g^{-1}.

Previous research has also indicated that cutting and shredding equipment can have microbial build-up issues (Garg et al., 1990; Ahvenainen, 1996; Buchholz et al., 2012; Castro-Ibanez et al., 2017; Allende et al., 2004; Buchholz et al., 2014). In 2001, a *Salmonella* outbreak from shredded lettuce in Queensland, AU was traced back to a contaminated shredder at a commercial processing plant (Stafford et al., 2002). Cutting equipment design improvement and innovation, such as water and sanitizer injection, could be explored for more efficient organic removal and a decreased probability of cross-contamination and increased bacteria reduction.

The population of aerobic mesophilic bacteria was significantly smaller (approximately 1.0 log g^{-1} decrease) for washed lettuce samples compared to cutter samples ($p < 0.05$), while there were no significant differences among cabbage samples. These results could be explained by the difference in water use during the flume cutting process. During cutting on the flume line, the cabbage processing line used water injection, while the lettuce line did not use water during cutting. The produce processor injected chlorinated water into the cutter to help

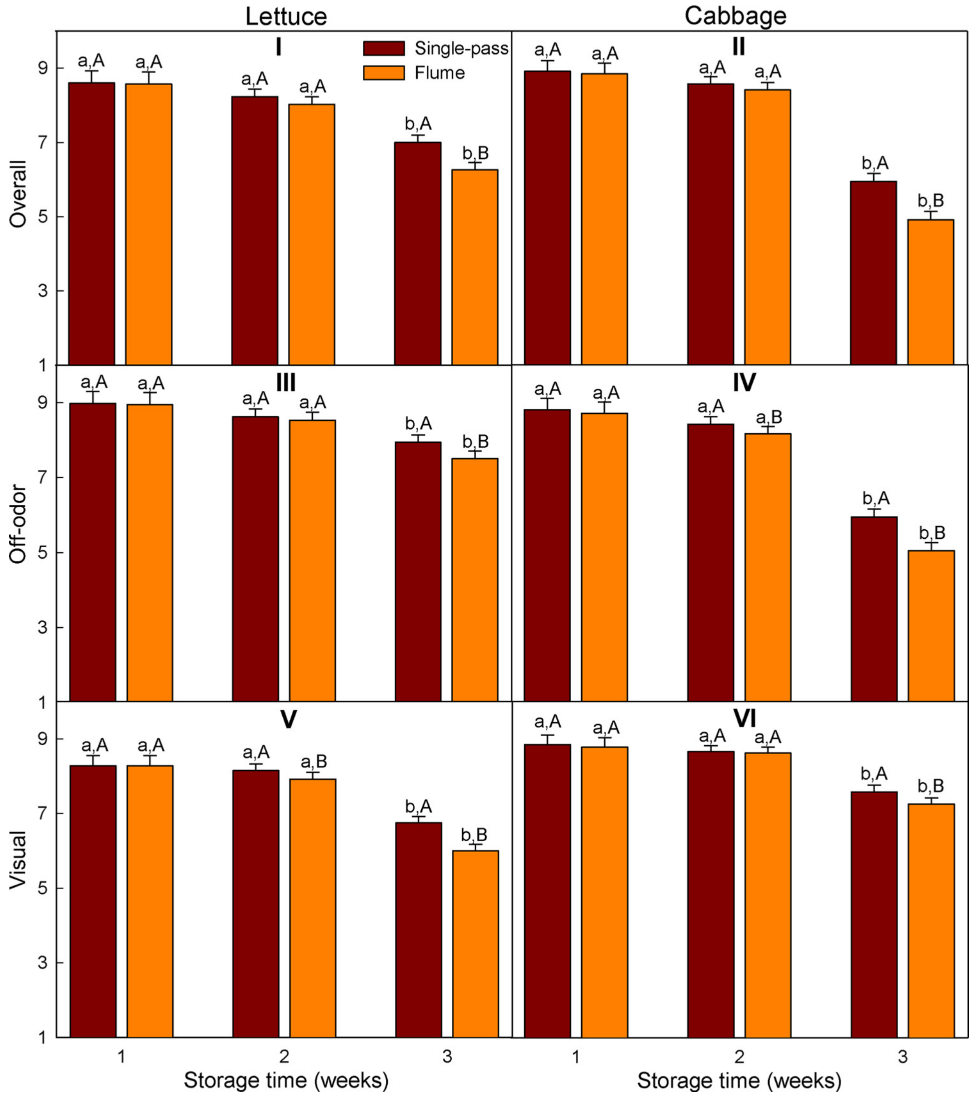

Fig. 4. Sensory ratings (average ± estimated standard error) for overall, olfactory, and visual acceptability of shredded lettuce (I, III, V) and diced cabbage (II, IV, VI) during storage at 1 °C using a 9-point hedonic scale (1 = dislike extremely, 9 = like extremely). Different lowercase letters show significant differences ($p < 0.05$) between storage times for each processing method. Different uppercase letters show significant differences ($p < 0.05$) between processing methods for each storage time.

remove pieces of diced cabbage from the blades and prevent a cutter jam. This use of water during the cutting may have reduced the aerobic mesophilic bacteria counts on the cut cabbage to a level that was not significantly different from the final product (washed cabbage); additional washing steps after the cutter in the flume and single-pass systems did not significantly reduce the bacterial counts on the cabbage. These findings imply that using water injection in the cutter may have other unintended benefits, such making it more difficult for bacteria to attach to the cut produce surfaces and blades. This further supports the idea that water (with or without sanitizer) injection in the cutter should be investigated in future studies.

Aerobic mesophilic bacterial population on the washed, final products from the flume and single-pass production lines were not significantly different; APC for the final products ranged from 3.2 to 3.4 log CFU g^{-1} for lettuce and 3.9 to 4.1 log CFU g^{-1} for cabbage, which is similar to previous studies (Ragaert et al., 2007; Delaquis et al., 2004). Furthermore, the final products from the single-pass and flume systems had similar quality scores during the first two weeks of storage at 1 °C ($p > 0.05$). After three weeks of storage, products from the single-pass system had significantly better quality ratings than those from the flume system. These positive sensory evaluations of single-pass products compared to flume products after longer storage times could be attributed to several factors. One possibility is that the single-pass, spray washing resulted in less organic materials remaining on the product surface to support bacteria growth.

The sensory attributes for all samples tested were in the marketable range (rating ≥6 'like slightly'), except for the olfactory and overall acceptability of the single-pass and flume washed cabbage after three weeks of storage. These results implied that both the single-pass and flume washed lettuce and cabbage could be stored for up to two weeks at 1 °C without noticeable quality differences. The flume system results agree with the findings form previous studies on the quality of fresh-cut leafy greens (Tudela et al., 2013; Luo, 2007; Kim et al., 2005b) and current industrial practice in the USA, which commonly uses a two-week shelf life for fresh-cut vegetables washed in flume systems. However, the quality and shelf life of fresh-cut produce washed in a single-pass system using on-site retreated water was previously unknown. Results from this study suggest that fresh-cut lettuce and cabbage washed using a single-pass system with on-site reclaimed water could also be stored for up to two weeks at 1 °C without significant quality deterioration; this was a critical finding from the sensory evaluation.

5. Conclusions

A unique single-pass washing system was compared to a typical double flume system within the same commercial fresh-cut manufacturer. The organic load indicators in the wash water samples from the single-pass system were consistent throughout 2.7 h of production, while the organic load indicators in the wash water from the flume system increased over time. By not directly reusing the spent wash water as is typical for flume systems, the single-pass system wash water was more controlled and had fewer issues with organic load build-up during production. Within the single-pass system, the wash water from the cutter had the largest population of aerobic mesophilic bacteria and the highest organic load indicators. This indicates that produce cutting is likely a critical step in cross-contamination prevention and organic material removal.

The aerobic mesophilic bacterial population on the produce washed in the flume and single-pass production lines were not significantly different, indicating that both processes were equally effective at reducing these bacteria on the final products. Lettuce and cabbage samples from the single-pass and flume systems had similar sensory ratings during the first two weeks of the shelf life study, which implied that products from either process could be stored for up to two weeks at 1 °C without noticeable quality differences. After three weeks of storage, lettuce and cabbage from the single-pass system had significantly better quality ratings compared to those from the flume system. This suggests that the single-pass system was at least as effective in maintaining food product quality and shelf life compared to the flume system. These findings could be used by the produce industry to optimize washing system operations and equipment designs for improved food safety, quality, and shelf life, while conserving water and reducing costs.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.postharvbio.2018.08.008.

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