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Modeling of the Effect of Washing Solution Flow Conditions on *Escherichia coli* O157:H7 Population Reduction on Fruit Surfaces

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ABSTRACT

Washing produce with sanitizing solutions is an important step in reducing microbial populations during postharvest handling. Little information exists regarding the effects of washing solution flow conditions on the efficacy of pathogen reduction during washing. This study was undertaken to investigate the effects of washing conditions such as flow velocity, agitation rate, and contact time on the reduction of *Escherichia coli* O157:H7 populations from the surfaces of cantaloupe rind and cut apples. Top surfaces of cylindrical samples were spot inoculated with *E. coli* O157:H7 and treated with peroxyacetic acid (POAA; 80 mg/liter) solution under different flow velocities and agitation rates and with different washing modes. Test results indicate that the reduction rate of *E. coli* O157:H7 increased with the increase in flow velocity and agitation rate under the testing conditions. In a 3-min treatment in the flow-through chamber, the *E. coli* O157:H7 count reduction on cantaloupe rind and cup apples reached 2.5 and 2.3 log CFU/cm^2, respectively, when the flow velocity increased from 0.0 to 0.8 m/min. Agitation conducted at the bottom of the treatment chamber reduced the *E. coli* O157:H7 population on cut apples by 1.2 log CFU/cm^2 in 3 min, whereas in the treatment with the agitation over the top of the chamber, the survival count of *E. coli* O157:H7 was reduced by only 0.8 log CFU/cm^2. The experimental data were used to fit four microbial reduction kinetic models. It was found that *E. coli* O157:H7 reduction from the fruit surfaces was best described by the Weibull model. These findings may be useful in designing produce wash systems for achieving enhanced pathogen reduction and improved produce quality and safety.

Produce wash is an important process employed commonly by the industry to remove soil and debris and to reduce microbial populations *(23).* Disinfectants such as chlorine, ozone, and chlorine dioxide are usually added in the wash water to increase the rate of microbial reduction and to prevent the potential cross-contamination of human pathogens during washing. Numerous studies have shown that the current commercial sanitizers used within the U.S. Food and Drug Administration–approved concentration can only achieve a 1- to 2-log CFU/g reduction in microbial populations *(12, 20).* There is a need to further improve the washing efficiency in order to increase the rate of reduction in human pathogens and improve the microbial safety of fresh produce.

In general, the rate of microbial reduction is affected by the type of sanitizers used *(11, 19, 30),* the mechanical force of washing *(18),* and the affinity of microorganisms with the produce surfaces *(8, 10, 24),* as well as the combination of all these factors. Many studies have described the efficacy of sanitizers on pathogen reduction *(1, 12, 24–26).* However, investigations regarding the effects of wash conditions, especially those related to washing solution flow conditions on microbial reductions, are limited.

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The effect of washing conditions on the removal of soil has been investigated in food plant sanitation studies, most of which are associated with the use of the cleaning-in-place method *(2, 7, 9, 14, 17, 28).* Sharma et al. *(21)* and Visser *(27)* reported the effect of flow hydrodynamics on the removal of soils on equipment surfaces. The cleanability of stainless steel surfaces soiled by *Bacillus* spores was investigated under different flow conditions by Faille et al. *(7)* and Leclercq-Perlat et al. *(13).* The reduction kinetics of *Bacillus cereus* spores from stainless steel surfaces in a cleaning-in-place treatment was modeled with a hyperbolic tangent function in the turbulent flow region *(15).* Dürr and Grasshoff *(6)* examined the mathematical background of a two-parameter Weibull model to describe a wet cleaning process.

Few studies have examined the effect of flow conditions on microbial reduction kinetics for biological surfaces, especially food surfaces. Dickinson and Cooper *(5)* investigated the attachment and detachment kinetics of *Staphylococcus aureus* on three protein-coated surfaces used for implanted and intravascular devices. They used first-order kinetic parameters to characterize the attached and detached cell populations. Bremer and Osborne *(3)* conducted 26 washing tests with king salmon and correlated the efficacy of bacterial reduction to chlorine concentration, flow rate, and duration of washing by a quadratic model. The re-

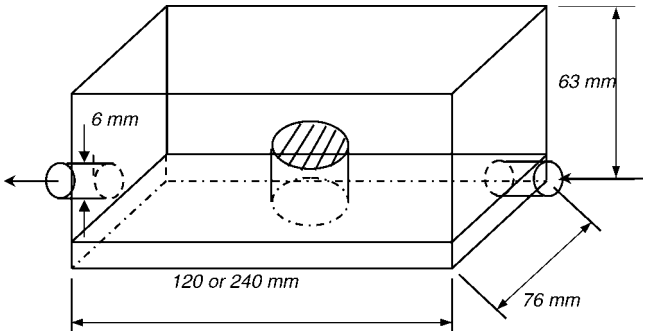

FIGURE 1. *Schematic drawing of flow-through washing chambers. Chamber 1 (C1) (120 mm in length by 70 mm in width by 63 mm in height) and chamber 2 (C2) (240 mm in length by 70 mm in width by 63 mm in height). The thickness of plastic sheet was 6 mm for the sidewall and 10 mm for the bottom.*

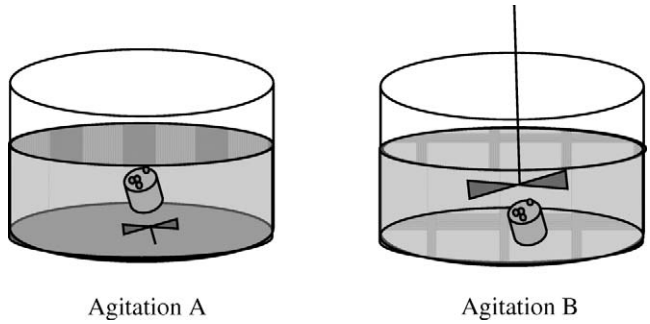

FIGURE 2. *Schematic drawing of agitation modes. Agitation mode A, agitation was conducted below the fruit samples in the water; agitation mode B, agitation was conducted above the fruit sample in the water.*

sponse surface methodology was utilized to predict the reduction of *Escherichia coli* O157:H7 from sprouts *(22).* Wang et al. *(29)* reported a dual-phasic inactivation behavior in tests with *E. coli* O157:H7 on fresh-cut apples and cantaloupe rinds when treated with three sanitizers at a fixed agitation speed (240 rpm). They used a first-order inactivation model in each phase to describe the inactivation kinetics. To our knowledge, there is no published report about the effects of different flow velocities or agitation rates on pathogen reduction from fruit and vegetable surfaces.

The objective of this study was to investigate the effects of washing conditions, including flow velocity, agitation rate, and treatment time, on the population reduction of *E. coli* O157:H7 from the surfaces of cantaloupe rind and fresh-cut apples washed with peroxyacetic acid solution (POAA). Four mathematical models were used to fit experimental data to determine correlations between washing conditions and pathogen reduction.

MATERIALS AND METHODS

Treatment chamber design. Two flow-through chambers (C1 and C2), which differed only in length, were designed and tested in this study (Fig. 1). Each chamber was used to hold one piece of cylindrical fruit sample. A circular recess (15-mm inside diameter, 10-mm height) was machined at the bottom of each chamber so that the sample could be embedded in it. The chamber was connected to a pump (Masterflex, model 7518-00, Cole Parmer, Vernon Hills, Ill.) by a piece of plastic hose (3-mm inside diameter) to provide an adjustable flow rate. The washing solution flowed at a selected average velocity over the upper surface of the sample, which projected upward 5 mm into the chamber. The flow velocity was estimated by dividing the volumetric flow rate of a sanitizer solution by the chamber cross-sectional area, expressed as $\nu = Q/S$, where ν was the average flow velocity (meters per second), S was the chamber cross-sectional area (square meters), and Q was the volumetric flow rate (cubic meters per second).

Agitation mode design. Agitation tests were conducted in fixed volume beakers. There were two agitation modes (A and B) designed to wash fruit samples at different agitation rates (Fig. 2). In agitation mode A, the wash solution was agitated with a stir bar placed below the samples and stirred with a magnetic agitator (Thermolyne Cimarec, Dubuque, Iowa). In agitation mode B, a blade agitator was inserted into the wash solution above the samples to provide the agitation.

Sample preparation. Golden delicious apples and cantaloupes were treated with UV light for 20 min to inactivate naturally occurring microorganisms on the fruit outer surfaces. Samples (15-mm diameter, 10-mm height) were prepared by first obtaining sample plugs with a sterilized brass cork-borer (no. 9, 15.5-mm inside diameter) and then cutting into the cylinders with a height of 10 mm with a sterile knife. The rind was retained on the top surface of the cantaloupe cylinders, but the skin was sliced off of the apple cylinders.

Inoculum preparation. A five-strain cocktail of *E. coli* O157:H7 (13B88, apple juice isolate; G5303, apple cider isolate; C7927, apple cider isolate; 204P, pork isolate; and EDL933, human feces isolate) was used in the study. Cultures recovered from frozen stocks were transferred three times to tryptic soy broth (pH 7.3; Difco, Becton Dickinson, Sparks, Md.) by loop inoculation at 24-h intervals and incubated at 37°C. After 24 h of incubation, bacterial cells were harvested by centrifugation (10,000 × *g*) at 4°C for 10 min. The cell pellets were washed twice in salt peptone (0.85% NaCl, 0.1% Bacto Peptone) and resuspended in 10 ml of 0.1% peptone water. Equal volumes (2 ml) of five cultures were mixed to obtain an inoculum (10 ml) containing approximately 10^8 CFU/ml of *E. coli* O157:H7.

Inoculation of sample. A 20-μl inoculum containing approximately 10^8 CFU/ml of *E. coli* O157:H7 was inoculated on the top surface, which was the rind for cantaloupes and the cut surface for apples, of a cylindrical sample. To ensure a relatively uniform inoculation, the 20-μl inoculum was distributed over 10 spots on the top surface of a cylindrical sample. The inoculated samples were air dried for 1 h at room temperature in a laminar flow biological hood (Labconco Purifier PCR Enclosure, Kansas City, Mo.) before washing.

Treatment procedure. Two experiments were conducted. In the first experiment, one piece of inoculated cylindrical sample was washed in POAA (80 mg/liter; Ecolab, St. Paul, Minn.) to compare the effect of washing time on *E. coli* reduction in two flow-through chambers (C1 and C2) at average flow velocities of 0.52, 0.65, and 0.80 m/min. The sample was analyzed at 0, 0.5, 1, 2, 3, 5, 8, and 15 min for the residual bacterial population.

In the second experiment, the inoculated cylinders were treated under two agitation modes (A and B) at a sample-to-liquid ratio (sample of about 7 g) of 1:14 (wt/vol), in which the samples were moved by the flow generated by the agitator. The inoculated

cylinders were also treated with POAA (80 mg/liter) under a continuous wash mode, as in the first experiment, facilitated by the flow-through chamber, where one piece of cylindrical sample was fixed to the bottom of the chamber. The continuous washing treatment was done in the flow-through chamber C1 in which POAA was passed over the top surface of the cantaloupe or apple sample for 3 min at average flow velocities of 0.0, 0.52, 0.65, 0.72, and 0.80 m/min. After the treatment, the samples were analyzed for residual bacterial population. The 3-min treatment time in the second experiment was chosen on the basis of the results obtained in the first experiment. All experiments were conducted at room temperature.

Bacteria enumeration. One cylindrical fruit sample was removed from the beaker or chamber at each selected sampling time, combined with 50 ml of sterile 0.1% peptone solution in a 400-ml sterile stomacher bag (Fisher Scientific Inc., Pittsburgh, Pa.), and blended with a Lab Blender 400 (Cooke Laboratory Products, Alexandria, Va.) for 4 min. The homogenate was filtered through sterile glass wool to remove fruit pulp fibers. A 100-μl sample of each filtrate was serially diluted in triplicate on sorbitol MacConkey agar supplemented with cefixime-tellurite (Oxoid Ltd., Basingstoke, Hampshire, UK). All such plates were incubated at 37°C for 24 h. For each plate, two typical *E. coli* O157:H7 colonies were chosen and identified by an *E. coli* O157 Latex Test (Oxoid Inc., Ogdensburg, N.Y.).

Modeling of *E. coli* O157:H7 reduction kinetics. The following models were used to fit the reduction kinetics.

(i) The first-order kinetic model

Under the assumption of identical resistance of all bacterial cells to both mechanical removal and killing caused by POAA, the residual survival count on the produce surface can be described by a log-linear model given by

$$\log N = \log N_0 - \frac{t}{D} \tag{1}$$

where N_0 is the initial population (CFU per square centimeter), N is the residual survival population at time t (CFU per square centimeter), and D is decimal reduction time (expressed in minutes).

(ii) The Weibull model

The Weibull model is used for describing non–log-linear microbial inactivation curves. It is based on the hypothesis that the resistance to stress of a population follows a Weibull distribution. It is given by the following equation:

$$\log N = \log N_0 - \left(\frac{t}{\alpha}\right)^{\beta} \tag{2}$$

where α is a characteristic time (expressed in minutes), and β is a shape factor.

(iii) The biphasic linear model

The biphasic linear model is also called a two-population model *(4)*. This model assumes that the population is split into two populations, which differ in their resistance to sanitizer and the ease in which they are removed from the surface during the washing step. The model was given by

$$\log N = \log N_0 + \log[(1 - f)10^{-t/D_h} + f10^{-t/D_l}] \tag{3}$$

where f represents tightly attached cells or cells with high resistance to POAA wash, D_h is the decimal reduction time of cells with high sensitivity to a sanitizer or mechanical removal (expressed in minutes), and D_l is the one with low sensitivity to the sanitizer or mechanical removal (expressed in minutes).

(iv) Hyperbolic tangent model

The hyperbolic tangent model was used by Lelievre et al. *(15)* to successfully describe the removal kinetics of *B. cereus* spores adhering to stainless steel surfaces. It is a three-parameter model given by the following equation *(15)*:

$$\log N = \log\left[a + (a - b)\tanh\left(\frac{t}{c}\right)\right] \tag{4}$$

where a is the amount of adhering cells at $t = 0$ (CFU per square centimeter), b is the plateau value (CFU per square centimeter), and c is relaxation time, which is inversely proportional to the reduction rate at $t = 0$ (expressed in minutes).

Model evaluation. The following three criteria were used to evaluate the different models.

(i) R^2

The R^2 values were calculated by the following:

$$R^2 = 1 - \frac{\text{SSE}}{\text{SST}} \tag{5}$$

where

$$\text{SSE} = \sum (Y_i - \hat{Y}_i)^2 \quad \text{and} \quad \text{SST} = \left(\sum Y_i^2\right) - \frac{\left(\sum Y_i\right)^2}{n}$$

The closer to 1 the R^2 values, the better the fit of the model *(4)*.

(ii) MSE

The mean square error (MSE) of the model is given by

$$\text{MSE} = \frac{\sum(\text{predicted} - \text{observed})^2}{n - p} \tag{6}$$

where n is the number of observations, and p is the number of parameters of the model. The lower the MSE, the better the adequacy of the model to describe the data *(16)*.

(iii) Accuracy factor

The accuracy factor (A_f) shows the accuracy of the model by comparing the average difference between observed and predicted values. The larger the value, the less accurate the model. A_f was calculated on the basis of the following equation:

$$A_f = 10^{1/n \,\Sigma\, |\log_{10}(\text{predicted value/observed value})|} \tag{7}$$

where n represents the number of sample points.

Statistical analysis. Each experiment was repeated three times, and triplicate samples from each treatment were analyzed at each sampling time. A one-way analysis of variance was performed for each experiment by the Statistical Analysis System (SAS Institute, Cary, N.C.). The Fisher least significant difference test was used to determine differences among means at $\alpha = 0.05$.

RESULTS AND DISCUSSIONS

Effects of washing time on *E. coli* O157:H7 population reduction from cantaloupe. The residual *E. coli* O157:H7 populations on the top surface (rind) of a cantaloupe cylinder treated with POAA for up to 15 min at different average flow velocities are presented in Figure 3. For

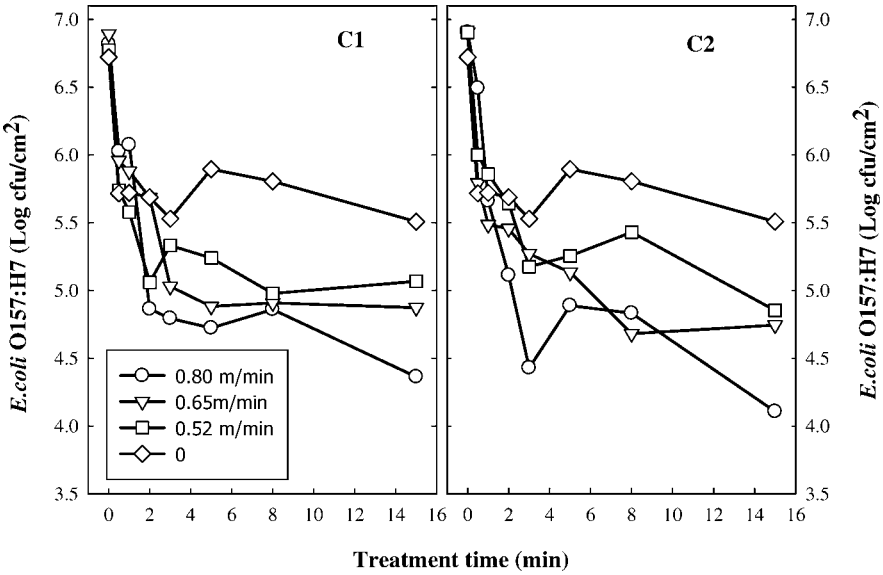

FIGURE 3. *Populations of* E. coli *O157:H7 remaining on the cantaloupe rind surfaces as influenced by the sanitizer solution flow velocity and contact time. Data represent the mean of three replications.*

the same flow velocity, no significant difference ($P < 0.05$) was found between C1 and C2 on residual bacterial count.

The sanitation treatment was merely a ''soaking'' process at 0 m/min, where no sheer force was present to help the bacterial removal from the fruit surfaces. It can be seen that this soaking treatment reduced the *E. coli* O157:H7 count by about 1 log CFU/g after a 30-s treatment in both C1 and C2 (Fig. 3). When a flow of the sanitizer was introduced, an additional reduction in the *E. coli* O157:H7 residual count was observed for all samples. The *E. coli* O157:H7 population reduction increased with an increase in flow velocity in both chambers. In the first 2 to 3 min, a relatively fast *E. coli* O157:H7 reduction was observed. After 3 min, however, extending the washing time did not result in significant increases in log reduction at each flow velocity. There was a fast microbial count reduction region and a slow reduction region on the curves of the washing tests. The statistic analysis showed that the log reduction in the fast reduction region for all the wash tests was significantly ($P < 0.05$) higher than in the slow reduction region. As suggested by Wang et al. *(29),* this biphasic washing behavior may be caused by the difference in the resistance of *E. coli* cells to a washing treatment. This finding may provide a guideline for improving an industrial produce-washing operation. A washing treatment in the slow reduction region is inefficient and should be avoided. It should be pointed out that the log reductions reported in this study were from the joint contribution of the bactericidal effect of POAA and the mechanical removal due to liquid flow.

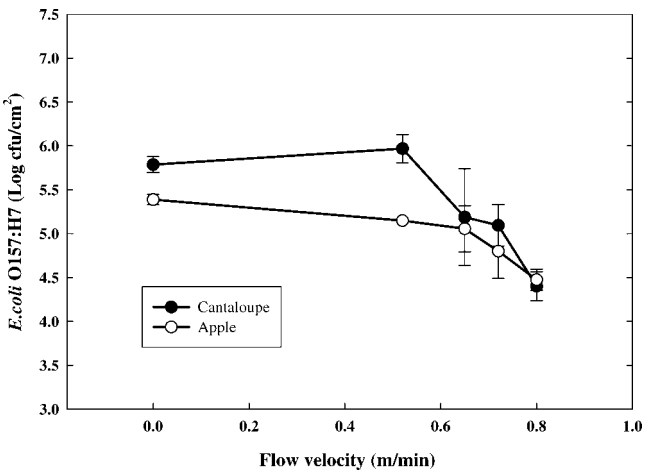

FIGURE 4. *Populations of* E. coli *O157:H7 remaining on cantaloupe rind and cut apple surfaces after washing with peroxyacetic acid (80 mg/liter) for 3 min at different average flow velocities (chamber C1). Data represent means ± standard deviations of three replications.*

Effects of washing mode on reduction of *E. coli* O157:H7 from fruit surfaces. The initial populations of *E. coli* O157:H7 inoculated on the surfaces of cantaloupe rind and fresh-cut apples were 6.9 and 6.8 log CFU/cm^2, respectively. A 3-min soaking-only treatment (in the absence of flow) resulted in 1.1- and 1.4-log reductions on surfaces of cantaloupe rind and fresh-cut apples, respectively. Increasing flow velocity enhanced *E. coli* O157:H7 population reduction on both fruits when the samples were washed with POAA (80 mg/liter) for 3 min in chamber C1 (Fig. 4). The log reduction on the two fruits increased to 2.5 and 2.3 log when the flow velocity reached 0.80 m/min. Because an increase in flow velocity is accompanied by an increase in sheer force *(14),* the observed improvement in *E. coli* O157:H7 reduction at a higher flow rate may be attributed to the more effective removal of adhered bacterial cells due to the greater sheer force. The log reductions of *E. coli* O157:H7 on cut apple surfaces were significantly higher ($P < 0.05$) than on cantaloupe when the flow rate of the wash solution was small (in the absence of flow and 0.52 m/min). However, this difference diminished when the flow velocity was increased to 0.65 m/min.

In agitation tests, the initial *E. coli* O157 counts, after inoculation, on the surfaces of cantaloupe rinds and fresh-cut apples were 6.6 and 6.8 log CFU/cm^2, respectively. In agitation mode A, there was a significantly ($P < 0.05$) higher *E. coli* O157:H7 population reduction from the cut apples when the agitation rates were at 240 and 400 rpm than in the absence of agitation (Fig. 5A). In agitation mode

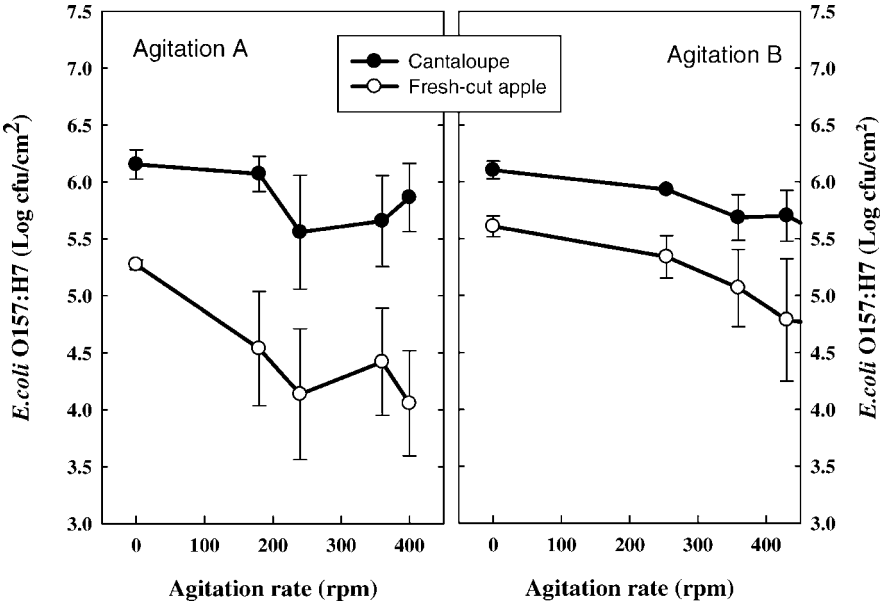

FIGURE 5. *Populations of* E. coli *O157:H7 remaining on cantaloupe rind and cut apple surfaces after washing with peroxyacetic acid (80 mg/liter) for 3 min at different agitation modes (A and B) and rates. Data represent means ± standard deviations of three replications.*

B, the increase in agitation rate was less effective for reducing *E. coli* O157:H7 on cut apples than in agitation mode A. A significantly ($P < 0.05$) higher *E. coli* O157:H7 population reduction was achieved on fresh-cut apples when the agitation rate was increased to 454 rpm than when agitation was absent (Fig. 5B). For cantaloupes, no significant difference ($P > 0.05$) was found in *E. coli* O157:H7 reduction with changes in agitation rate in either agitation mode A or B. A larger *E. coli* O157:H7 reduction rate was found on cut apple surfaces than on cantaloupe surfaces under agitation mode A. This finding was in agreement with our earlier study *(29),* in which the scanning electron microscopy images of cantaloupes and apples showed different surface morphologies. The dry and irregularly pitted rind may have helped the *E. coli* O157:H7 cells to better attach to rind surface and better protect them from being reached by POAA during washing. Relatively large standard deviations in washing tests can be observed in Figures 4 and 5. In the flow-through test, only one piece of cylindrical sample was used. This small sample size may have caused the large variation in the log reduction reported. In addition, the variation in biological materials may have played a role. Results presented in Figures 4 and 5 illustrate the effects of flow velocity and agitation rate on *E. coli* population reduction. It can be seen that an increase in flow velocity or agitation rate in produce washer design will help increase the bacterial reduction rate. An optimized combination of sanitizer flow pattern, flow velocity, and treatment time may help improve washing efficiency in a produce sanitizing process.

TABLE 1. *Statistic indices of microbial removal models for washing with POAA at different washing modes*

			Removal models[a]			
Fruit	Washing mode	Statistic index	Linear	Weibull	Biphasic linear	Hyperbolic tangent
Cantaloupe	Flow chamber	R^2	0.4581	**0.9194**	0.2402	0.2012
		MSE	0.2791	0.0622	1.1742	1.2342
		A_f	1.0023	1.0001	1.0158	1.0046
	Agitation A	R^2	0.4211	0.4739	**0.5036**	0.4084
		MSE	0.0508	0.0692	0.1307	0.1558
		A_f	1.0020	1.0002	1.0003	1.0005
	Agitation B	R^2	0.9282	**0.9456**	0.9282	0.6658
		MSE	0.0038	0.0044	0.0115	0.0540
		A_f	1.0007	1.0001	1.0008	1.0002
Fresh-cut apple	Flow chamber	R^2	0.7097	**0.9794**	0.2694	0.4391
		MSE	0.0471	0.0050	0.3558	0.2731
		A_f	1.0030	1.0010	1.0480	1.0012
	Agitation A	R^2	0.7277	0.8794	**0.8883**	0.8324
		MSE	0.0840	0.0562	0.1042	0.1563
		A_f	1.0090	1.0005	1.0005	1.0008
	Agitation B	R^2	0.9151	**0.9953**	0.9151	0.5818
		MSE	0.0149	0.0012	0.0446	0.2197
		A_f	1.0028	1.0001	1.0028	1.0002

[a] Boldface type indicates the best fit for the treatment among four models.

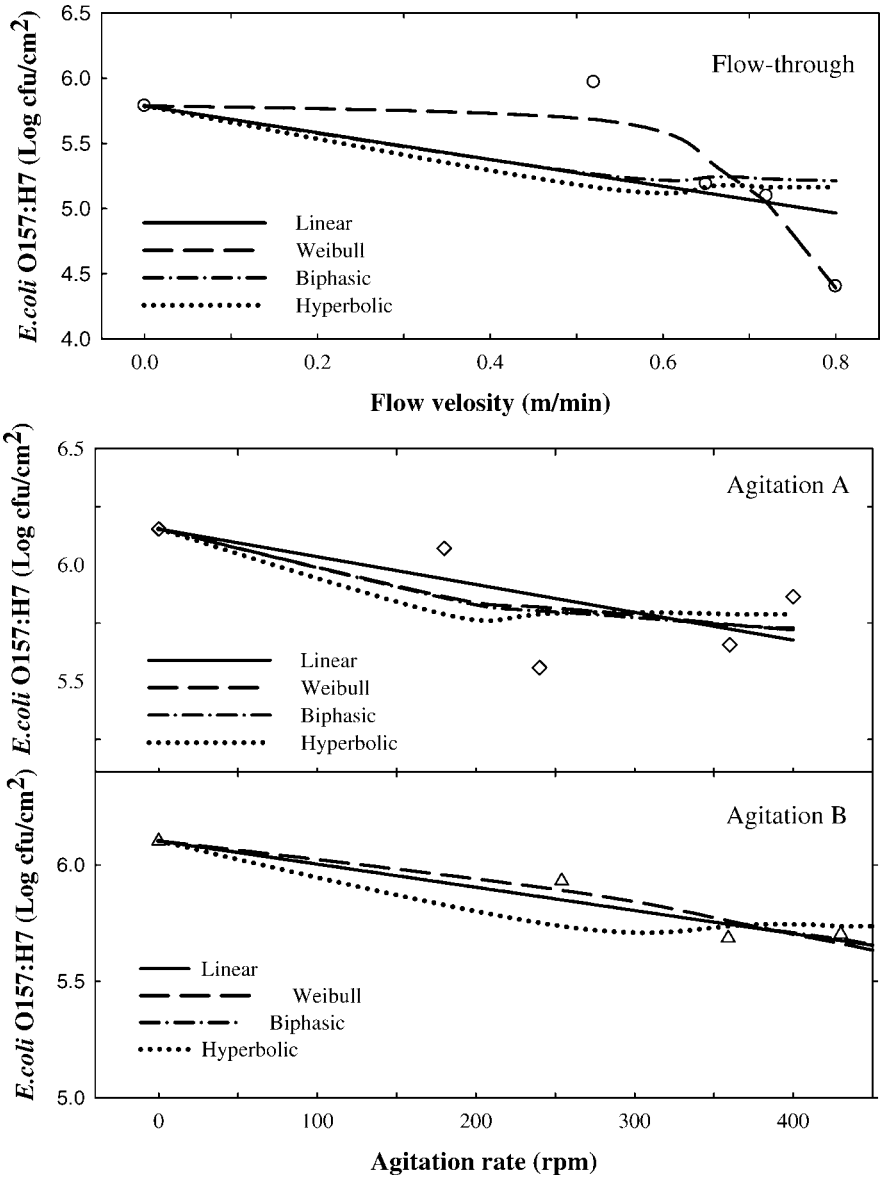

FIGURE 6. *Modeling of* E. coli *O157:H7 reduction on cantaloupe rind after washing with peroxyacetic acid (80 mg/liter) solution at different flow velocities, agitation modes (A and B), and agitation rates.*

Washing treatments with POAA may involve different microbial reduction mechanisms for the agitation methods and the flow-through method. The flow in the flow-through chamber was generated by a pump and was parallel to the sample top surface. In addition, because the cylindrical sample was fixed to the bottom of the chamber and was motionless, the average flow velocity estimated from the flow rate of the pump was thus the absolute velocity for POAA flowing over the sample top surface. In the tests with an agitator, however, the samples moved with the flow generated by the agitator, and hence, the absolute fluid velocity over the sample surface was lower than the velocity of the bulk fluid, which made it difficult to quantify. The difference in the absolute fluid velocity over sample surfaces and the flow patterns between the flow-through and agitation arrangements, as well as the surface topology, may have affected the ability of POAA to remove microbes trapped in pores and crevices. More studies are needed to fully understand the effects of these factors.

TABLE 2. *Parameter estimates of the Weibull model for washing with POAA at different washing modes*

Fruit	Washing modes	α	β
Cantaloupe	Flow chamber	0.7570	6.024
	Agitation A	2123	0.5004
	Agitation B	776.2	1.388
Fresh-cut apple	Flow chamber	0.8225	3.964
	Agitation A	286.6	0.332
	Agitation B	468.4	1.991

Assessment of model adequacy on effects of washing conditions on *E. coli* O157:H7 population reduction. Data from experiments were fitted to four models to determine the correlation between residual populations of *E. coli* O157:H7 and flow velocity–agitation rates. Figure 6 illustrates the fit between experimental data and the four models for cantaloupe-washing tests. Table 1 shows the goodness-of-fit as described by R^2, MSE, and A_f values for the four models. Except for agitation mode A, the model based on Weibull distribution yielded high R^2 values (0.8794 to

TABLE 3. *Statistic indices of microbial removal models for washing at different average flow velocities*

Chamber	Flow velocity (m/min)	Statistic index	Removal models[a]			
			Linear	Weibull	Biphasic linear	Hyperbolic tangent
Chamber 1	0	R^2	0.1814	0.8914	**0.9003**	0.8886
		MSE	0.0590	0.0375	0.0343	0.0381
		A_f	1.0112	1.0001	1.0006	1.0020
	0.52	R^2	0.3382	**0.9368**	0.8842	0.7991
		MSE	0.1899	0.0428	0.0572	0.0651
		A_f	1.0336	1.0081	1.0171	1.0293
	0.65	R^2	0.4982	**0.9162**	0.8128	0.5921
		MSE	0.3155	0.0902	0.1677	0.2567
		A_f	1.0381	1.0090	1.0235	1.0493
	0.80	R^2	0.5220	**0.8612**	0.7723	0.4889
		MSE	0.4690	0.1463	0.2270	0.2980
		A_f	1.0590	1.0255	1.0437	1.0813
Chamber 2	0	R^2	0.1814	0.8914	**0.9003**	0.8886
		MSE	0.0590	0.0375	0.0343	0.0381
		A_f	1.0112	1.0001	1.0006	1.0020
	0.52	R^2	0.5343	**0.9322**	0.8846	0.6516
		MSE	0.1802	0.0600	0.2359	0.5240
		A_f	1.0282	1.0051	1.0149	1.0370
	0.65	R^2	0.5268	**0.9769**	0.9301	0.7158
		MSE	0.1600	0.0231	0.1701	0.5884
		A_f	1.0262	1.0013	1.0100	1.0347
	0.80	R^2	0.5529	**0.8462**	0.7377	0.4351
		MSE	0.5417	0.2184	0.9083	1.4479
		A_f	1.0567	1.0217	1.0416	1.0890

[a] Boldface type indicates the best fit for the treatment among four models.

0.9794), low MSE values (0.0012 to 0.0692), and low A_f values (1.0001 to 1.0010) and hence best described the reduction of *E. coli* O157:H7 cells from fruit surfaces. The poorly fitting performance of the log-linear model indicated the existence of cells with different resistances to the washing treatments. The hyperbolic tangent model that has been successfully used to model a cleaning-in-place cleaning process *(15)* also yielded a poor fit with low R^2 values (0.2012 to 0.8324). The biphasic model provided a better fit to data from the agitation treatments with relatively high R^2 (0.5036 to 0.9282) and low MSE (0.0115 to 0.1307) and low A_f (1.0003 to 1.0480) values. However, it failed to describe the *E. coli* O157:H7 population reduction for data from the flow-through washing tests. The parameter estimates in the Weibull model are listed in Table 2. All microbial population reduction curves exhibited a relatively large deviation from the log-linear relation ($\beta = 1$). The shape factors (β) for flow chamber–washing tests were greater than 3.964, indicating the existence of a shoulder in the inactivation curve.

TABLE 4. *Parameter estimates of the Weibull model for washing at different average flow velocities*

Chamber	Flow velocity (m/min)	α	β
Chamber 1	0	0.7326	0.02
	0.52	0.1539	0.13
	0.65	0.4746	0.2
	0.80	0.4614	0.3
Chamber 2	0	0.7326	0.02
	0.52	0.5838	0.2
	0.65	0.2351	0.2–1
	0.80	0.4570	0.3

Assessment of model adequacy on effect of washing time on *E. coli* O157:H7 population reduction. Data fitting techniques were also used to find best-fit models for washing in two chambers at different average flow velocities. Similar to the findings in Table 1, the Weibull model generated a best fit as shown by a high R^2 (0.8914 to 0.9769), low MSE (0.0231 to 0.2184), and low A_f (1.0001 to 1.0255) (Table 3). The biphasic linear model yielded a fit better than the log-linear and hyperbolic models. The parameter estimates for the Weibull model are tabulated in Table 4. It can be seen that the Weibull model generated a best fit at all flow velocities in the two chambers. The biphasic model, however, gave a better fit for the absence-of-flow treatment (0 m/min) as shown by high R^2 and relatively low MSE and A_f values. The biphasic model better described the microbial reduction caused by POAA when the flow velocity was zero. This suggests that the biphasic model is good for microbial reduction caused by one lethal factor, which, in the present study, was the *E. coli* O157:H7 cells having different resistance to POAA treatment in the soaking mode. When a flow was introduced into a treatment chamber, cells with different resistance to the mechanical removal would also affect the *E. coli* O157:H7

population reduction rate. The Weibull model seemed more flexible in handling microbial reduction involving multiple mechanisms.

In summary, the sanitizer solution flow hydrodynamics that resulted from different washing modes differentially affected the reduction of *E. coli* O157:H7 from fruit surfaces. For the same washing mode, increasing flow velocity of the POAA solution decreased viable *E. coli* O157:H7 populations on fruit surfaces. Extending washing time was only effective in reducing microbial count in the first 2 to 3 min of washing. The *E. coli* O157:H7 reduction rate from cantaloupe and cut apple surfaces was best described by the Weibull model. Selection of an optimum combination of sanitizer solution flow pattern, flow velocity, and washing time is necessary to further improve the washing efficacy in the reduction of bacterial populations from fruit surfaces.

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