CPS CENTER for PRODUCE SAFETY

CPS 2017 RFP
FINAL PROJECT REPORT

Project Title
Mathematical modeling tools for practical chlorine control in produce wash process

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Objectives
The main research objective is to construct data-informed models that quantitatively link easy-to-measure water quality parameters to commodity-specific organic load and free chlorine (FC) decay kinetics during recirculated wash conditions. The above objective will be realized via the following tasks for green cabbage and carrots (various cut types for each produce type):

Task 1: Build mathematical models that take into account wash water chemistry, commodity specific aspects.

Task 2: Validate model predictions against lab and pilot-plant scale data.

Funding for this project provided by the Center for Produce Safety through:
CPS Campaign for Research

FINAL REPORT

Abstract
Produce washing is an important step in the supply chain which is intended to improve safety; however, maintaining adequate sanitizer control at the commercial level is still a technical challenge. To address this issue, this project focused on developing mathematical models that can predict free chlorine (FC) decay dynamics during recirculated wash conditions. Model parameters, relative to cut carrots or green cabbage, were determined during single-batch washing experiments at the 3L scale. Using only these parameters and chemical oxygen demand (COD) dynamics as inputs, the models were able to successfully predict FC decay under continuous produce washing and periodic replenishment conditions at both the 3L and 50–100L scales. Supplemental model validation, in the context of cut/shredded iceberg lettuce wash data, showed successful FC decay predictions at both the lab (3L, 100L) and pilot (3200L) scale. It was further shown, using Spearman rank correlation coefficients, that turbidity and total dissolved solids (TDS) measurements are not reliable predictors of FC decay kinetics.

Background
As globalization has broadened the fresh produce supply chain and increased its complexity, more sophisticated methods of surveillance are needed to ensure the safety of fresh products. In particular, the processing juncture is a critical control point that has received much attention. *While many wash systems are being used in good faith and according to standard protocols, it is clear that a greater understanding of in-practice dose measurement in relation to water quality constituents and commodity-specific parameters is needed.* Part of the problem is that the relationships between sanitizer levels and water quality parameters have been described mainly through experimental and correlative approaches or by risk models that are difficult to parameterize accurately. While these results are important, they alone cannot be used to make precise predictions, or for taking real-time corrective measures in dynamic circumstances. Accordingly, there is an *urgent need* to mathematically describe the fundamental dynamics that generate the observed relationships between sanitizer levels and water quality parameters. Not meeting this need represents a serious problem because, without clear scientific foundations informing sanitizer control, the increased demand for fresh produce translates into increased potential for widespread foodborne disease outbreaks.

Research Methods and Results

Objective 1: *Build mathematical models that take into account wash water chemistry and commodity specific aspects*

Mathematical model:
Using chemical reaction theory for chlorination reactions and chemical oxygen demand (COD) information to estimate organic load, the loss of FC due to organics in the wash water can be modeled. To describe the FC decay kinetics in the process water, an ordinary differential equation system was built that relies on (I) wash operation specifics such as tank volume, produce type and wash time, and discharge of rate of produce into the wash tank as well as (II) chlorine chemistry. Type (II) details are determined by the fact that for the majority of chlorination reactions, the elementary reaction can be formulated as HOCl + B → Products, where B is an organic or inorganic compound (Deborde and von Gunten, 2008, Water Research 42:13–51). The basic model equations are as follows:

$$\frac{d\vec{O}}{dt} = \sum_{n=1}^{N} k_n \chi_{[t_{n-1},t_n]} \vec{\gamma} - F(\vec{\beta}, \vec{O}, C) \quad (1)$$

$$\frac{dC}{dt} = g(\vec{\beta}, \vec{O}, C), \qquad (2)$$

where the derivatives above are with respect to time t (min); $\vec{O}$ (mg/L) represents the organic load (relative to the cut produce type, which is assumed to enter the wash tank at a rate proportional ($\vec{\gamma}$) to the change in COD (mg/L)); N is the number of batches washed; k_n (mg/(L min)) represents the change in COD; χ is the indicator function (taking on values 1 when produce is being washed and 0 otherwise); C (mg/L) is the FC level in the wash water; F and g are forms for chlorine reactions with organics; and $\vec{\beta}$ (L/(mg min)) represents apparent reaction rate constants.

Note that while $\vec{\beta}$ is a function of pH, however, for all data used to build/validate the models, this variable will be effectively fixed during experimentation by using citric acid. Furthermore, note that the parameters in model (1)-(2) are tailored to commodity/cut for respective produce types.

Method to determine model parameters:
Produce/cut types:
Carrots (imperator type) and green cabbage were purchased from a local supermarket and stored at 4°C and used for experiments within two days of purchasing. Exterior leaves of the cabbage were trimmed out and discarded. Cut specifications were as follows: 1”x1” for cabbage; 0.25” x 0.25” x 1” for stick carrots; and 0.25” thickness for disk carrots.

Single-batch wash procedure:
Experiments for single-batch washing were carried out in a 3L wash water system. Before starting each experiment, 1.4 ml of concentrated (4.5%) sodium hypochlorite (BCS Chemicals, Redwood City, CA, USA) was added to the wash tank to achieve approximately 20 mg/L FC in the wash water. The pH was simultaneously adjusted to 6.5 using 1 M citric acid. Produce (100 g; carrots, cabbage) was put into a sieve, submerged in 3 L of tap water (20°C), and washed (via manual agitation) for 30 seconds; the sieve was then held over the 3 L of wash water for another 30 seconds. Water quality parameters (FC, pH, and COD) were measured just before and after washing as well as periodically for 30 min following washing. This procedure was repeated three times for disk carrots, stick carrots and cabbage, respectively.

Using a modified version of model (1)-(2), the data from the single-batch wash experiments and a least squares fitting technique (using the function *fminsearch*, MATLAB, 2018a, The MathWorks, Natick, 2018), the model parameters $\vec{\gamma}$ and $\vec{\beta}$ were determined relative to each produce/cut type.

Objective 2: ***Validate model predictions against lab data across multiple scales***

In order to test the model equations (1)-(2) predictive ability, three types of experiments were performed: batch produce washing with a single FC dose at the 3L scale, batch produce washing with multiple FC doses at the 3L scale, and continuous produce washing with multiple FC doses at the 50–100L scale.

Small-scale experiments (3L):
Experiments for a single FC dose (i) were carried out in a 3L wash water system. Before starting each experiment, 1.4 ml of concentrated (4.5%) sodium hypochlorite (BCS Chemicals) was added to the wash tank to achieve approximately 20 mg/L FC in the wash water. The pH was simultaneously adjusted to 6.5 using 1 M citric acid. Different types of cut produce (600 g;

stick & disk carrots, cabbage) were washed in each experiment through 6 batches, each consisting of 100 g. The dwelling time for each batch was 30 seconds. Water samples were taken and analyzed before the first wash and after each successive wash. Experimentation for each produce/cut combination was done in triplicate.

Experiments for multiple FC dosing (ii) were also carried out in a 3L wash system. Essentially, the procedure followed that described for (i) above but for 3 separate runs. That is, about 1.4 mL of (4.5%) sodium hypochlorite was added to the wash tank to achieve approximately 20 mg/L free chlorine in the wash water. The pH was simultaneously adjusted to 6.5 using 1 M citric acid. 600 g of different types of cut produce (carrots/cabbage) were washed in each experiment through 6 batches, each consisting of 100 g. Directly after the first run of washing 600 g of produce, the FC was replenished (via the addition of sodium hypochlorite) to reach approximately 20–25 mg/L and the pH was again adjusted to 6.5. The procedure above was followed until 1200 g of produce was washed batch-wise and then the FC was replenished a final time, with the pH adjusted to 6.5 and the final 600 g of produce was washed. Thus 1.8 kg of produce was washed for each trial with 3 runs.

Water quality measurements for experiments with regards to both (i) and (ii) included: FC and total chlorine, COD, turbidity, TDS, and pH. FC was measured immediately after each batch based on a DPD (N,N-diethyl-p phenylenediamine) method using a chlorine photometer (CP-15; HF Scientific Inc., Ft. Myers, FL). The pH, turbidity, and TDS were measured on-site using a digital pH meter, turbidity meter (Aquafast, Thermo Orion, Beverly, MA), and TDS meter, respectively. The COD was determined using a reactor digestion method.

Larger-scale experiments (50–100L):

Procedure for carrots:

Carrots (15 kg) were sliced using a mandolin slicer to 1/8-inch-thick and kept in sterilized containers immediately prior to being discharged into a wash tank (100 L of tap water) at a rate of 0.5 kg/min. The experiment consisted of three 10-min runs, simulating a continuous wash operation with periodic replenishment of sodium hypochlorite. In each run, 5 kg of carrots was washed. Before the start of the first run, 60 ml of concentrated (4.5%) sodium hypochlorite was added to the wash tank to achieve approximately 21.5 mg/L FC washing solution. The pH was simultaneously regulated at 6.5 using citric acid. During washing, the carrot pieces were submerged into the water manually and washed for 30 seconds and then removed via sieves. Water quality (COD, pH, turbidity and TDS) and FC concentration were measured every 2 min (as described for the small-scale experiments). After finishing the first run, the FC level was replenished by adding 30 ml of concentrated (4.5%) sodium hypochlorite and the pH was also set on 6.5 by adding citric acid. The experiment resumed after 5 min, and samples were collected every 2 min for the second segment. Similarly, after finishing the second run, 50 ml of concentrated (4.5%) sodium hypochlorite was added to the tank and the pH adjusted to 6.5 using citric acid, and the same procedure was repeated for the third run.

Procedure for cabbage:

Cabbage (15 kg) was chopped using a chopper to 1”x1” pieces and kept in sterilized containers immediately prior to being discharged into a wash tank (50 L of tap water) at a rate of 0.5 kg/min. The experiment consisted of three 10-min runs, simulating a continuous wash operation with periodic replenishment of sodium hypochlorite. In each run, 5 kg of cabbage was washed. Before the start of the first run, 20 ml of concentrated (4.5%) sodium hypochlorite was added to the wash tank to achieve approximately 13.5 mg/L FC washing solution. The pH was simultaneously regulated at 6.5 using citric acid. During washing, the cabbage pieces were submerged into the water manually and washed for 30 seconds and then removed via sieves. Water quality (COD, pH, turbidity and TDS) and FC concentration were measured every 2 min (as described for the small-scale experiments). After finishing the first run, the FC level was replenished by adding 15 ml of concentrated (4.5%) sodium hypochlorite and the pH was also set on 6.5 by adding citric acid. The experiment resumed after 5 min, and samples were collected every 2 min for the second segment. Similarly, after finishing the second run, 20 ml of concentrated (4.5%) sodium hypochlorite was added to the tank and the pH adjusted to 6.5 using citric acid, and the same procedure was repeated for the third run.

Results:

Using the commodity specific model parameters $\vec{\gamma}$ and $\vec{\beta}$ (which were determined ***only*** from the data obtained from single-batch wash experiments as described in Objective 1), and COD data (used to inform the change in COD, k_n, after each batch of produce washed) as inputs, model (1)-(2) was able to successfully predict the FC decay kinetics at both the 3L (for both single and replenishment FC dosing experiments) and 50–100L scales.

<u>3L experiments:</u>

Table 1 summarizes the model's performance against FC decay data during produce (disk/stick carrot and cabbage) washing with FC replenishment at the 3 L scale, listing R^2 values for each respective run as well as a total R^2 value considering the 3 runs of each respective experiment together. Figures 1-3 provide a clear visual of the model's predictive success for the respective produce/cut types at the 3 L scale.

<u>50–100L experiments:</u>

For these larger-scale, continuous wash experiments, 50 L of water was used for cabbage and 100 L of water was used for disk carrots, respectively. Using the same parameter values for $\vec{\gamma}$ and $\vec{\beta}$ (as used to test against the 3L data) and only COD input, model (1)-(2) was again able to successfully predict the FC decay kinetics. The results are summarized in Table 2. Figure 4 illustrates the model's prediction versus data for disk carrots at 100L, and Figure 5 illustrates the model's success for cabbage washing at the 50L scale.

Key findings:

- The results in Tables 1 and 2 (and Figures 1–5) indicate that model (1)-(2) captures the main mechanisms governing observed FC decay relative to the produce/cut type.
- FC reaction rates relative to produce/cut type appear to be robust with respect to scaling, as the same rates used by the model at 3 L and 50–100 L resulted in accurate predictions.
- COD information is a relatively consistent predictor of the associated produce/cut type organic load in wash water and therefore a fairly reliable predictor (via the model) of FC decay rates.

Objective 3: *Validate model predictions against pilot-scale data*

Pilot scale/commercial data (relative to cabbage/carrots) collected by Dr. Yaguang Luo's lab (USDA, Beltsville) was initially to be used to test the model at an operative scale that is more reflective of high-speed industrial produce washing. However, key input information concerning the FC dosing scheme used during these experiments was unable to be determined and therefore that data was not utilized.

Nevertheless, Dr. Luo supplied our team with water quality data from her pilot-scale study on washing shredded iceberg lettuce, which corresponded with clear, quantifiable FC dosing procedures. To further evaluate the model's ability to predict FC decay across multiple scales, we conducted iceberg lettuce wash experiments (for 1''x1'' pieces) at the 3L and 100L scales, following similar experimental procedures as outlined in Objective 1 and Objective 2.

Results:

Following the fitting procedure in Objective 1, the model parameters $\vec{\gamma}$ and $\vec{\beta}$ (for a single-wash batch) were determined for iceberg lettuce. These values were then used in the model to predict FC decay at 3 L and 100 L (for FC replenishment experiments) and at 3200 L (Dr. Luo's pilot-scale data). Table 3 and Figure 6 (3L scale) as well as Table 4 and Figure 7 (3200L scale) illustrate the quality of the model's predictions at the respective scales (the 100L results are not shown in the report as these are similar to the 3L scale results). Note that for the 3L and 100L iceberg lettuce experiments, the wash water temperature was 20°C and the lettuce cut size was 1"x1" whereas during the pilot-scale experiments the water temperature was about 5°C and the lettuce was shredded.

Key findings:

- FC reaction rates associated with iceberg lettuce (cut/shredded) washing appear to be robust with respect to scaling, as the same rates used by the model at 3 L, 100 L and 3200 L resulted in accurate predictions.

Objective 4: ***Quantitatively link easy-to-measure water quality parameters (turbidity and/or TDS) to commodity-specific organic load and FC decay kinetics***

Note that the success of the model predictions (as discussed in Objectives 2 and 3) depends on the fact that the change in organic load (relative to produce/cut type) was quantified via a model that utilizes only the successive change in COD information rather than just current COD levels. Unfortunately, real-time COD measurements are not currently feasible during produce washing and therefore surrogate parameters that can be measured in real-time are needed. Let ∂X denote "change in X". The observation above, regarding the success of the model (1)-(2), indicates that a correlative relationship between ∂TUR and ∂COD or ∂TDS and ∂COD be determined. That is, we seek functions U and T such that ∂COD = $U(\partial$TUR$)$ and ∂COD = $T(\partial$TDS$)$. Furthermore, it is logical that these functions be monotonic (i.e., an increase in the input corresponds to an increase in the output).

To evaluate if functions U and T can be determined in practice, wash data for carrots/cabbage obtained at both the 3L and 50–100L levels (from procedures in Objective 2) was utilized. In particular, the Spearman's rank correlation coefficient (ρ) between (a) ∂TUR and ∂COD and (b) ∂TDS and ∂COD for respective produce types and experimental runs was calculated. Essentially, ρ indicates how well the connection between two variables can be described by a monotonic function (not necessarily linear).

Using the *corr* function in MATLAB, the corresponding ρ value for each experimental run and across respective experiments was calculated. The results are presented in Tables 5 and 6 (3L scale) and Tables 7 and 8 (50–100L scale), providing strong evidence that there is no consistent relationship between ∂TUR and ∂COD or between ∂TDS and ∂COD for cut carrots/cabbage across the scales considered. Furthermore, selected data are included to provide visual evidence towards the variability that exists between these quantities (see Figures 8 and 9 for disk carrots at the 3L scale, and Figures 9 and 10 for cabbage at the 50L scale).

Key findings:

- For cut carrot/cabbage washing, neither TDS nor turbidity are consistent predictors for informing FC decay kinetics.

Outcomes and Accomplishments

1. Mathematical models, based on commodity specifics, wash operation details, and chemical reaction theory that can predict FC decay kinetics were developed. Using COD information relative to washing various carrot/cabbage cut types, the models were validated at scales from 3 to 100 L. Also, the model's FC decay predictions were validated for cut/shredded iceberg lettuce operations ranging from a 3L lab scale to a 3200L pilot scale.

2. The CSU team is currently preparing a manuscript to be submitted.

3. Following the June 2018 CPS Research Symposium, the CSU team started discussions with food safety experts at Dole to evaluate particular FC strategies at a commercial scale.

Summary of Findings and Recommendations

1. Because the FC decay predictions hold at multiple scales, the models developed from this project illustrate *fundamental chlorine decay dynamics that occur during fresh-cut carrot/cabbage and iceberg lettuce washing*. In particular, this gives validity to performing future lab-scale experiments to quantify FC decay associated with different produce/cut types as well as experiments aimed at understanding the impact of continuous FC dosing on FC dynamics during produce washing.

2. The CSU team found that *turbidity and TDS measurements are not reliable in predicting FC levels*, as there is no consistent, observable relationship linking the increase in organic load (in terms of COD) from cut carrots/cabbage entering the wash tank (3–100 L) and the corresponding increase in turbidity or TDS. Similar results were observed for cut/shredded iceberg lettuce across various scales (3 L, 100 L, and 3200 L). In particular, the model's predictive success across scales and produce types provides a strong case that COD information is much more reliable than that of turbidity or TDS.

3. The results from this research demonstrate the utility of using mathematical models as tools to elucidate fundamental mechanisms, like FC reaction rates associated with various produce cut types. To minimize expensive experiments at a commercial scale, these models and key lab-scale experiments can aid in planning the logistics of how and what should be measured during commercial-scale experimentation. For instance, for models, like those developed in this project, to be effective tools in validating FC control at the industrial scale, FC data collected at the commercial scale must include *quantifiable* FC input and water replenishment information.

APPENDICES

Publications and Presentations

No published papers at this time but at least one manuscript is in preparation.

Submitted abstract:
Abnavi M, Munther D, Kothapalli C, Srinivasan P. A mathematical model for chlorine kinetics and pathogen cross-contamination in fresh produce wash process. IAFP 2019 Annual Meeting, Louisville, Kentucky.

Budget Summary

Project funds awarded to CSU team: $48,747.00

The funds for this project were used in the following ways:

- Tuition and salary for graduate students (just under half of the funds).
- Lab equipment: turbidimeter, pH meter, reactor (COD), colorimeter (FC), TDS meter, water filtration system, balance, pipette controller, produce cutting equipment
- Consumables: carrots, cabbage, lettuce, water, chlorine, pipettes, gloves, tips, COD digestion vials, biochemistry reagents, disposable containers, accessories/materials for equipment above
- Travel: PI to June 2018 CPS Symposium , PI/co-PI to visit to Dole facilities (Soledad, CA), PI/Co-PI to attend June 2019 CPS Symposium

Tables and Figures

See below for Tables 1–8 and Figures 1–11.

Table 1. Results of model prediction (given as R^2 values) for FC replenishment dosing experiments at 3L scale.

Produce	Experiment	Run 1	Run 2	Run 3	Total
Stick	1	0.68	0.94	0.99	0.929
Stick	2	0.95	0.99	0.95	0.963
Disk	1	0.99	0.98	0.79	0.936
Disk	2	0.97	0.97	0.76	0.892
Disk	3	0.99	0.97	0.84	0.948
Cabbage	1	0.72	0.85	0.99	0.873
Cabbage	2	0.99	0.99	0.96	0.978
Cabbage	3	0.99	0.95	0.89	0.938

Table 2. Results of model prediction (given as R^2 values) at 50–100L scale.

Disk carrots	**Run 1**	**Run 2**	**Run 3**
R^2	0.99	0.99	0.93
Cabbage	**Run 1**	**Run 2**	**Run 3**
R^2	0.78	0.98	0.94

Table 3. Model results for predicting FC decay associated to 1”x1” cut iceberg lettuce at 3 L (given as R^2 values).

Produce	Experiment	Run 1	Run 2	Run 3	Total
Iceberg	1	0.99	0.98	0.94	0.965
Iceberg	2	0.98	0.99	0.99	0.989

Table 4. Model results for predicting FC decay associated to shredded iceberg lettuce at 3200 L (given as R^2 values).

R^2	Run 1	Run 2	Run 3	Total
Experiment 1	0.96	0.99	0.91	0.972
Experiment 2	0.98	0.98	0.95	0.980
Experiment 3	0.98	0.99	0.97	0.988

Table 5. Spearman's rank correlation coefficient ρ for ∂COD vs ∂TUR data from experiments at the 3L scale.

Produce	**Experiment**	**Run 1**	**Run 2**	**Run 3**	**Total**
Stick	1	-0.2018	0.800	-0.3078	-0.1628
Stick	2	-0.800	-0.200	-0.400	-0.4055
Disk	1	0.149	0.3714	-0.029	0.1376
Disk	3	0.4569	-0.1218	0.5385	0.3659
Cabbage	1	0.3714	-0.4928	-0.1160	0.1894
Cabbage	3	-0.3361	0.381	0.2101	0.2699
Iceberg	1	0.3353	0.700	-0.2319	0.1402
Iceberg	2	0.2224	0.7143	0.8469	0.4011

Table 6. Spearman's rank correlation coefficient ρ for ∂COD vs ∂TDS data from experiments at the 3L scale.

Produce	**Experiment**	**Run 1**	**Run 2**	**Run 3**	**Total**
Stick	1	0.8333	-0.400	-0.800	-0.1052
Stick	2	-0.800	0.800	0.6669	0.3282
Disk	1	-0.1177	0.3381	0.6269	0.4054
Disk	3	0	-0.1674	-0.2582	-0.0181
Cabbage	1	0	0.8454	-0.1791	0.3119
Cabbage	3	-0.7307	0.2520	-0.1967	0.0274
Iceberg	1	0.0782	0.2887	0.1852	0.2191
Iceberg	2	-0.3203	-0.0976	0.1456	-0.0884

Table 7. Spearman's rank correlation coefficient ρ for ∂COD vs ∂TUR data from experiments at the 50L scale for cabbage, and 100L scale for disk carrots and iceberg. * indicates significance where p-value < 0.05.

Produce	**Experiment**	**Run 1**	**Run 2**	**Run 3**	**Total**
Disk	1	0.300	0.100	0.100	0.2538
Cabbage	1	-0.300	-0.600	0.100	-0.1251
Cabbage	2	0.8208	-0.100	0.500	0.0413
Iceberg	1	-0.6325	-1.00	0.400	-0.1053
Iceberg	2	-0.6669	0.300	-1.00*	-0.4293

Table 8. Spearman's rank correlation coefficient ρ for ∂COD vs ∂TDS data from experiments at the 50L scale for cabbage, and 100L scale for disk carrots and iceberg. * indicates significance where p-value < 0.05. NaN indicates no number returned for ρ.

Produce	**Experiment**	**Run 1**	**Run 2**	**Run 3**	**Total**
Disk	1	0.7071	0.7182	0.5798	0.4080
Cabbage	1	0	-0.2887	-0.8660	-0.3233
Cabbage	2	0.8652	0.7379	0.2887	0.5911*
Iceberg	1	NaN	-0.4472	0.2582	0.1913
Iceberg	2	-0.1579	-0.3536	-1.00*	0.0088

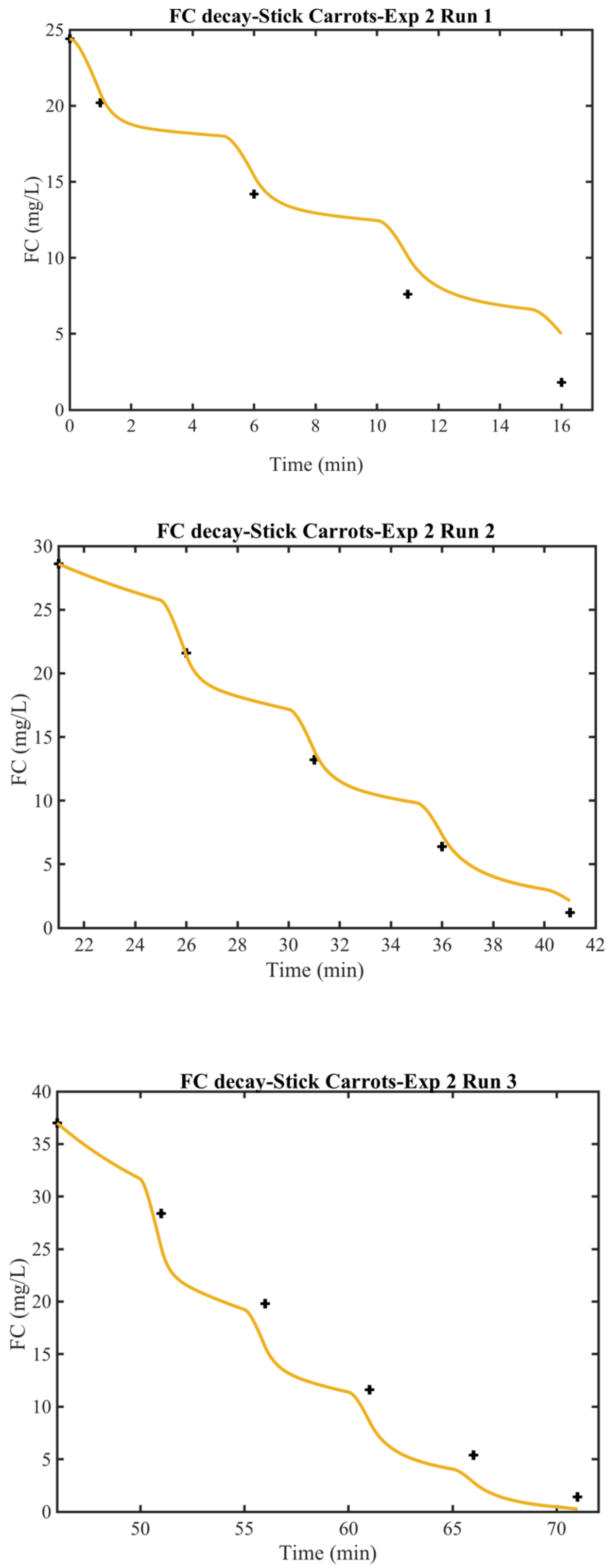

Figure 1: Model prediction of FC decay kinetics for stick carrots at 3 L, Experiment 2. The solid line is the model prediction and the data points are FC measurements. Refer to Table 1 for R^2 values.

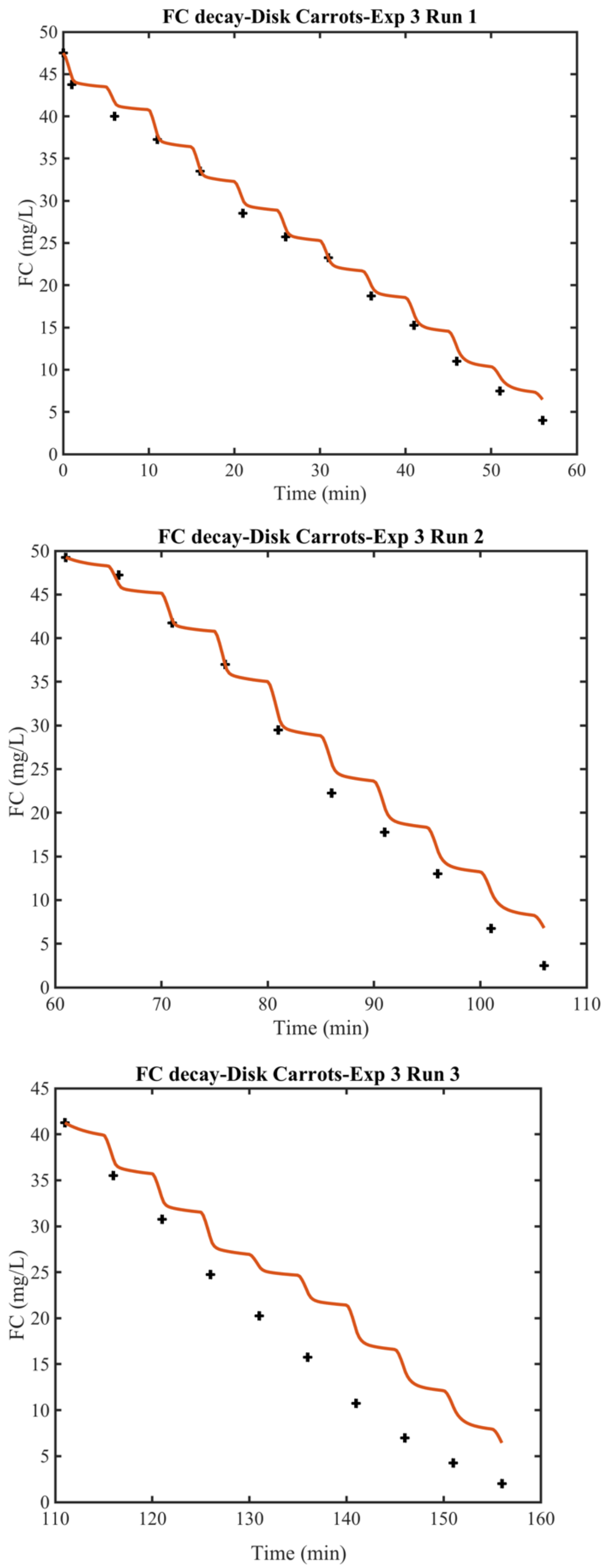

Figure 2: Model prediction of FC decay kinetics for disk carrots at 3 L (batch-wash experiments). The solid line is the model prediction and the data points are FC measurements. Refer to Table 1 for R^2 values.

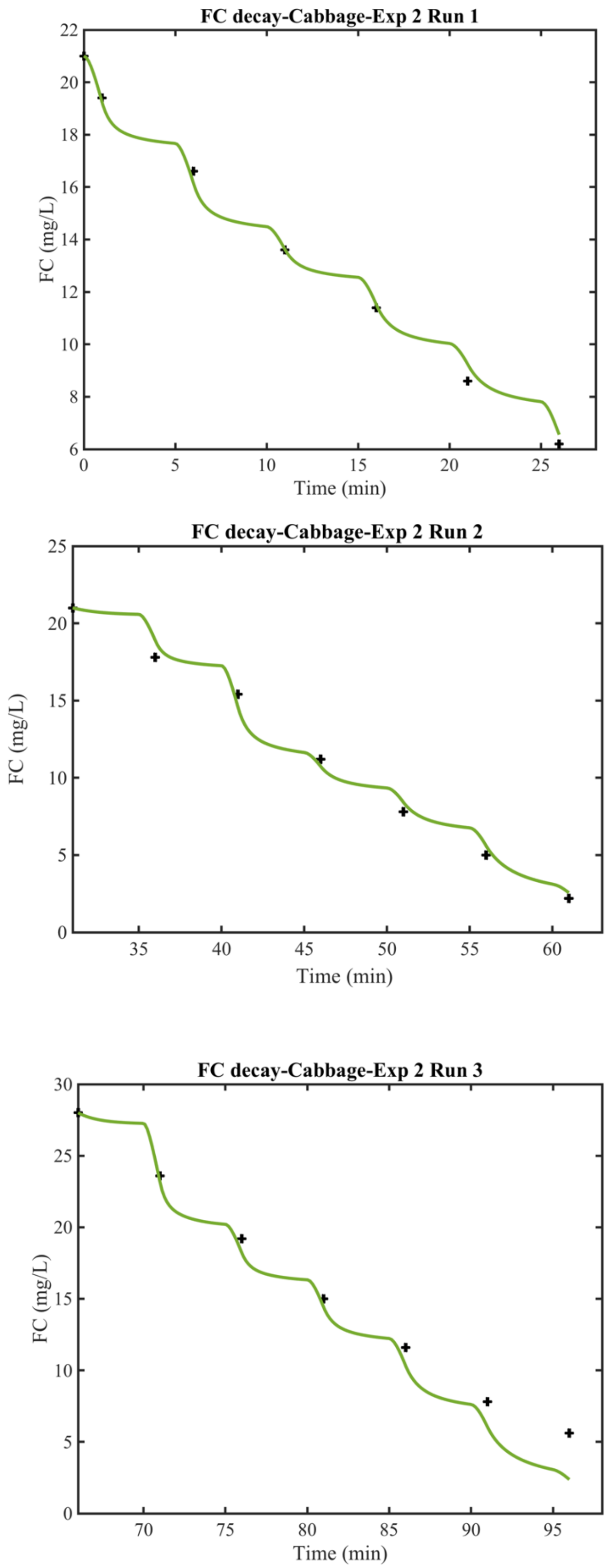

Figure 3: Model prediction of FC decay kinetics for cabbage at 3 L (batch-wash experiments). The solid line is the model prediction and the data points are FC measurements. Refer to Table 1 for R^2 values.

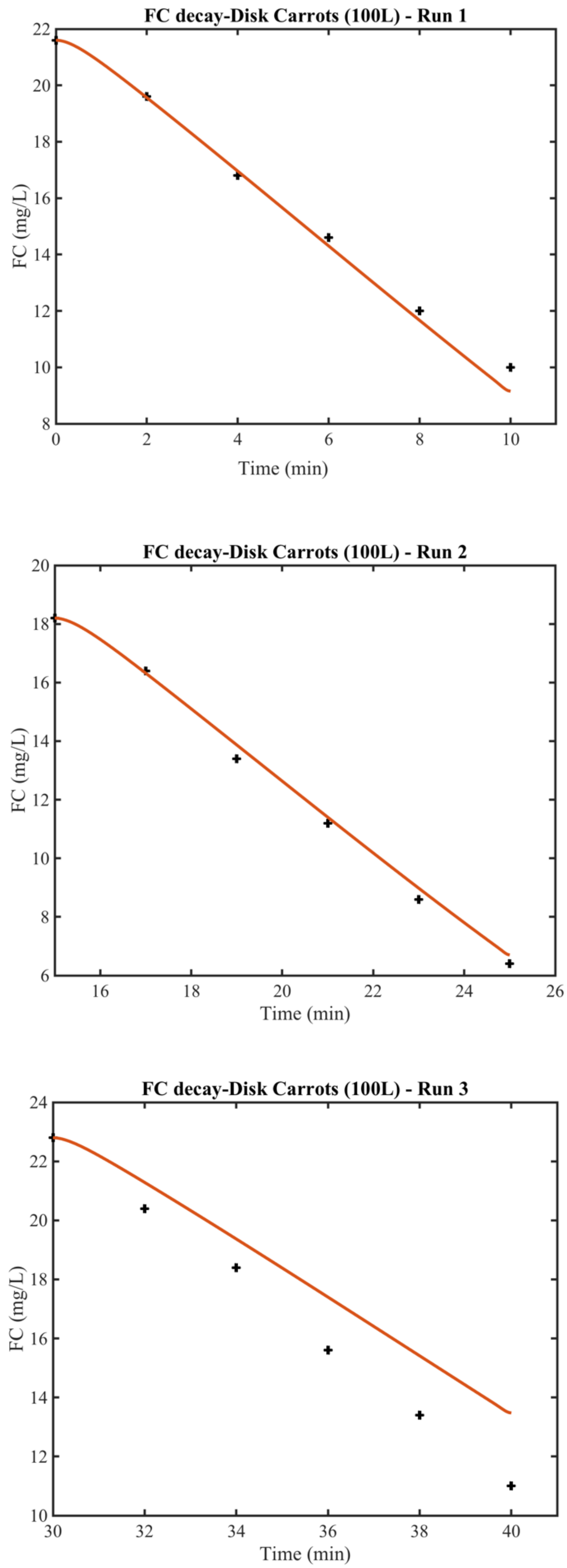

Figure 4: Model prediction of FC decay kinetics for disk carrots at 100 L (continuous wash experiments). The solid line is the model prediction and the data points are FC measurements. Refer to Table 2 for R^2 values.

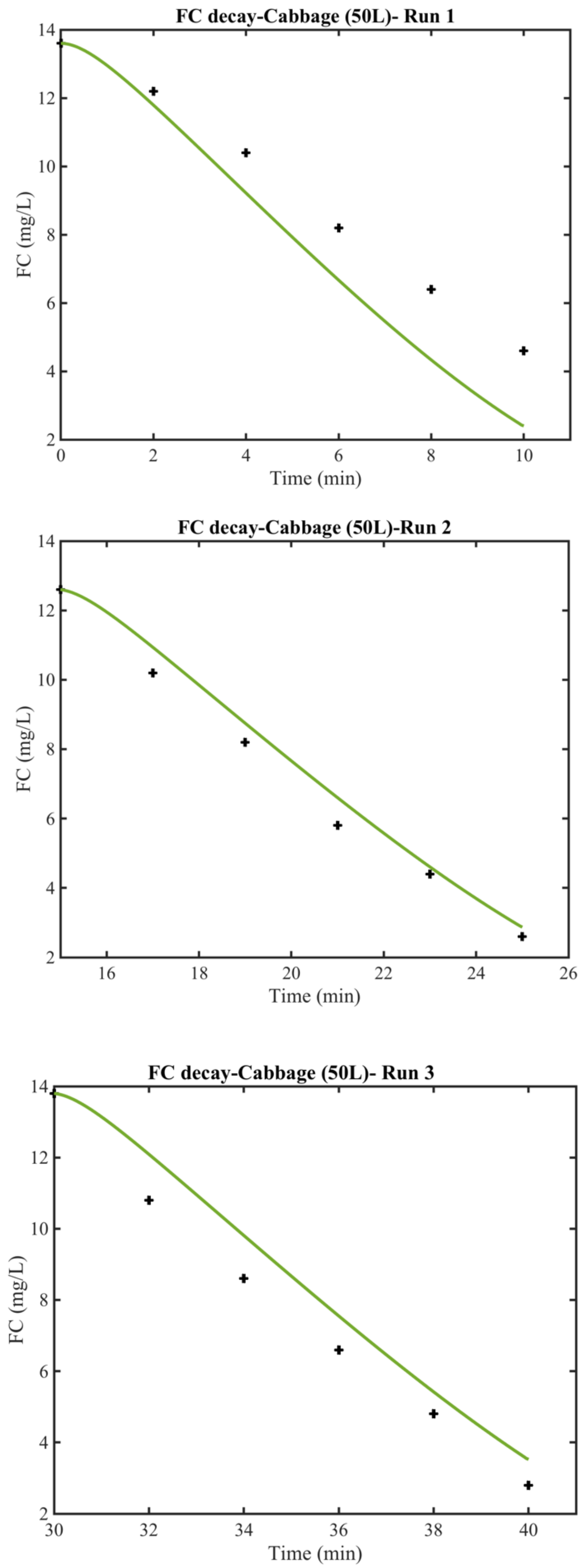

Figure 5: Model prediction of FC decay kinetics for cabbage at 50 L (continuous wash experiments). The solid line is the model prediction and the data points are FC measurements. Refer to Table 2 for R^2 values.

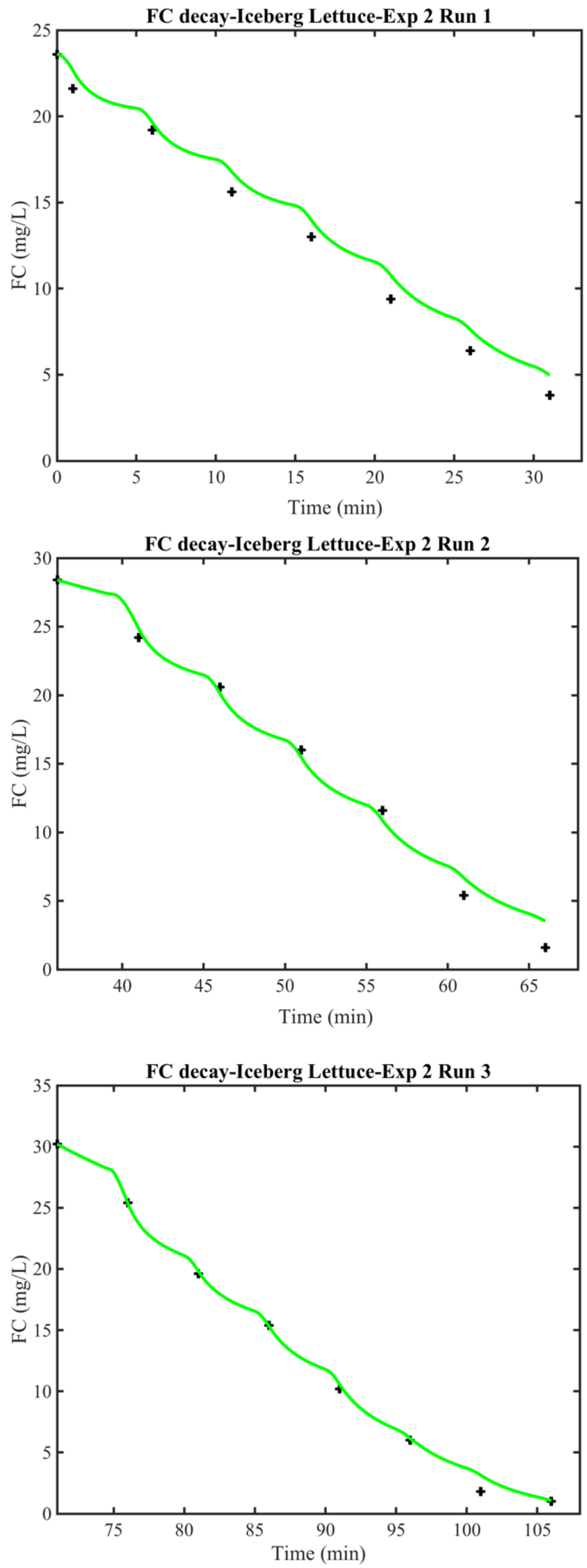

Figure 6: Model prediction of FC decay kinetics for iceberg lettuce at 3 L (batch-wash experiments). The solid line is the model prediction and the data points are FC measurements. Refer to Table 3 for R^2 values.

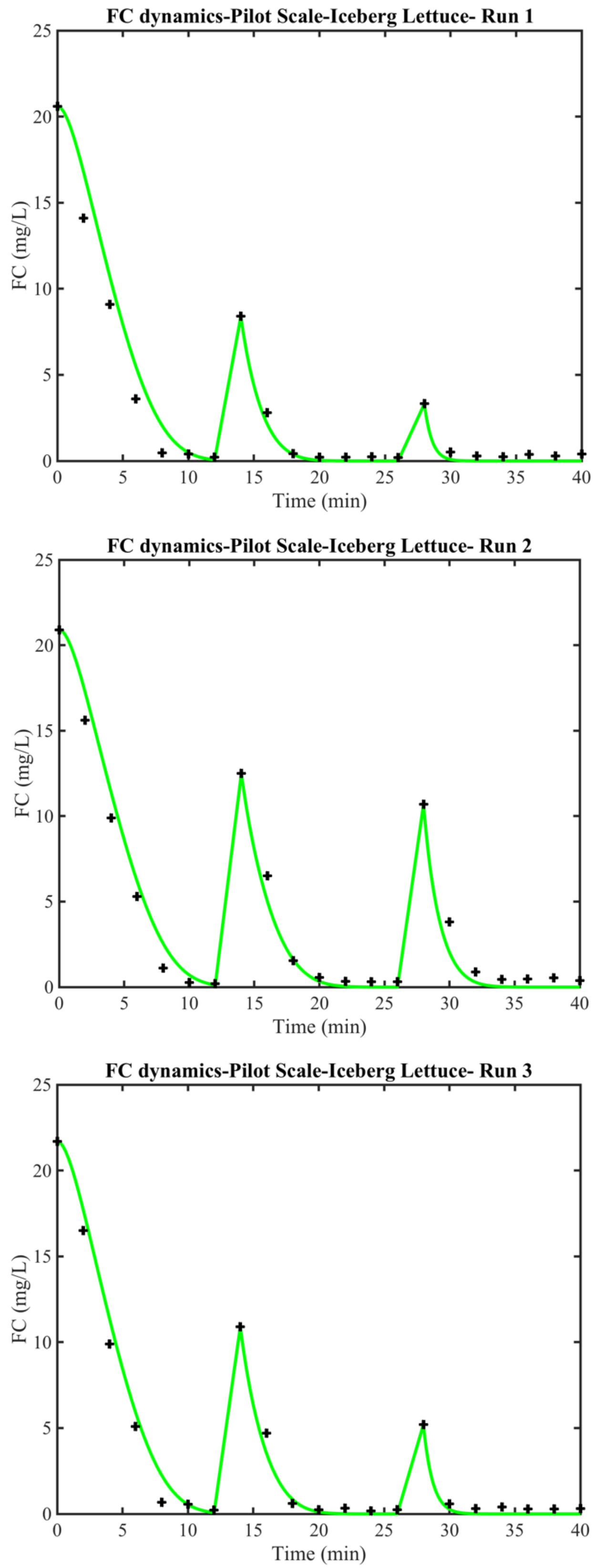

Figure 7: Model prediction of FC decay kinetics for shredded iceberg lettuce at 3200 L. The solid line is the model prediction and the data points are FC measurements. Refer to Table 4 for R^2 values.

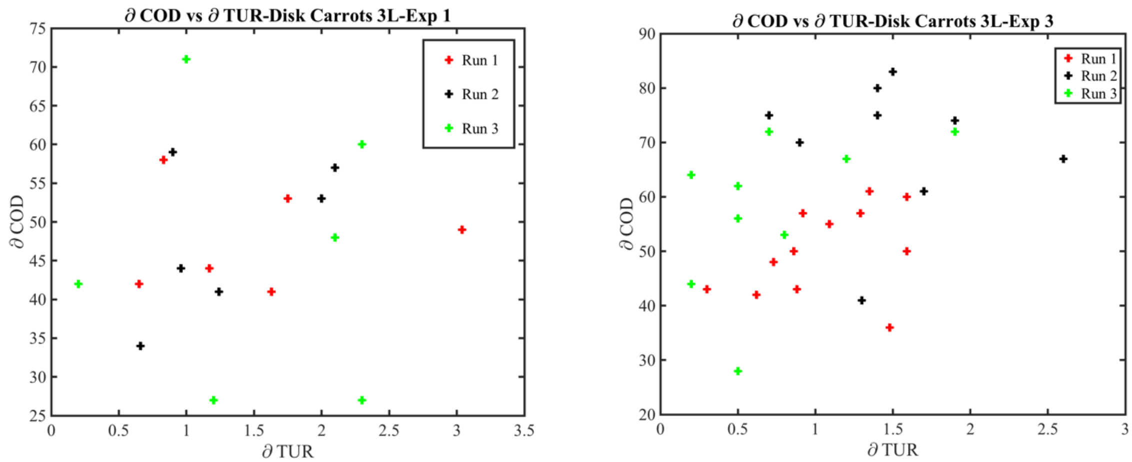

Figure 8: ∂COD vs ∂TUR data associated with washing disk carrots at 3 L (experiments 1 and 3).

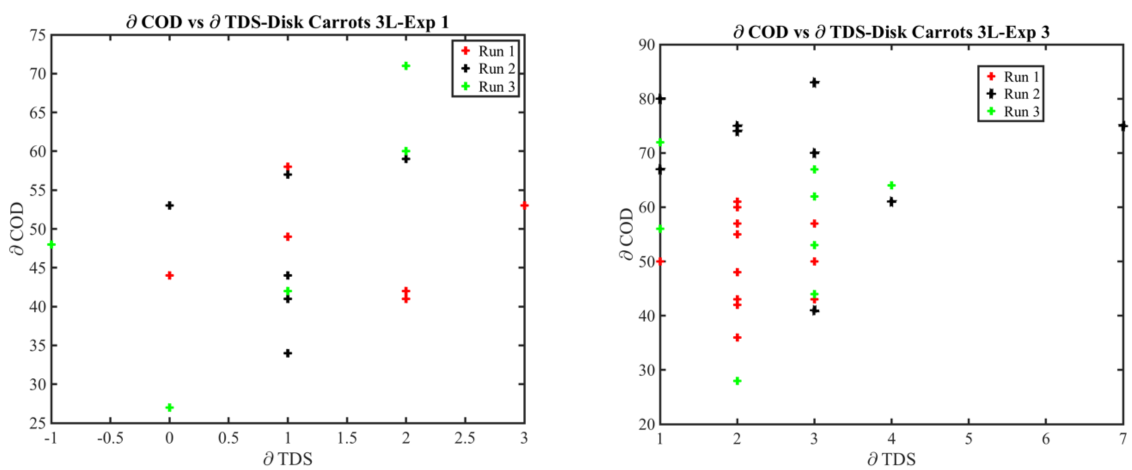

Figure 9: ∂COD vs ∂TDS data associated with washing disk carrots at 3 L (experiments 1 and 3).

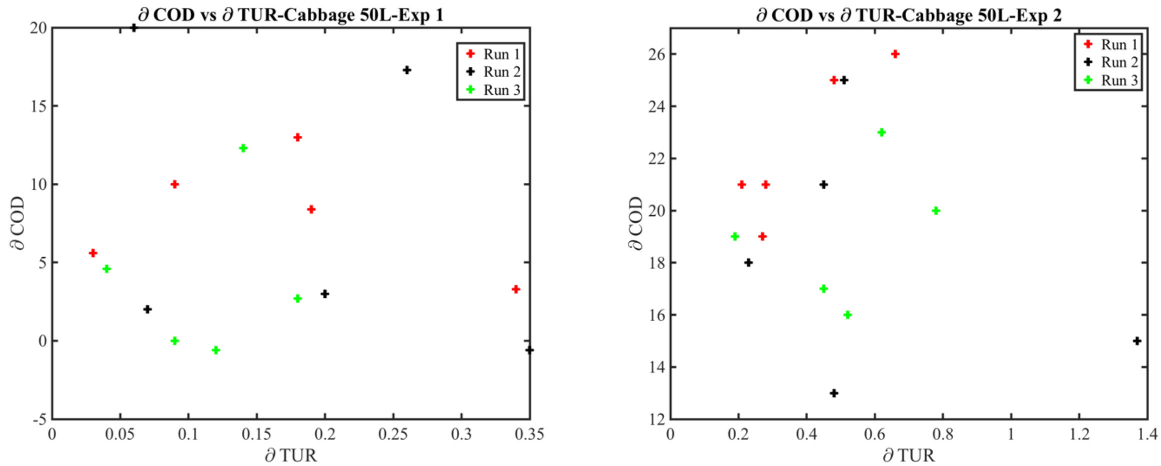

Figure 10: ∂COD vs ∂TUR data associated with washing cabbage at 50 L (experiments 1 and 2).

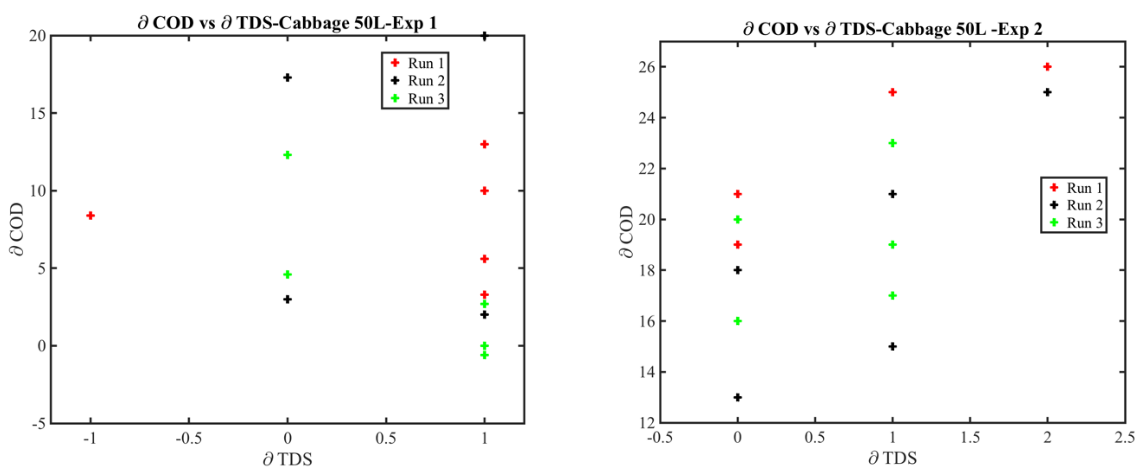

Figure 11: ∂COD vs ∂TDS data associated with washing cabbage at 50 L (experiments 1 and 2).