Fruit and vegetable wash-water characterization, treatment feasibility study and decision matrices

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ABSTRACT

On average, it is estimated that up to 5 liters of wastewater is generated per kg of produce in post-harvest processing of fruit, leafy greens and root vegetables. The typical wastewater parameters vary in concentration (solids content, COD, BOD, nitrogen, phosphorus) based on the produce being processed. The challenge for producers and regulators is that the selection of the appropriate treatment technology is challenging, so decision matrices were developed to narrow down the treatment selections. Wash-waters for different types of fruit and vegetables from two different operation types, washing only vs. washing and processing. Bench-scale treatments selected for testing included settling, coagulation and flocculation with settling, centrifuge, dissolved air flotation, electrocoagulation, screening, and hydrocyclone. The developed decision matrices summarize the removal effectiveness of the different treatments for typical wastewater parameters and serve as a reference tool in understanding wash-water treatment technologies and their effectiveness in treating various wash-waters.

keywords: fresh-cut fruits and vegetables, wash-water, treatment technology, solids reduction

1 Introduction

The fresh-cut fruit and vegetable sector continues to grow due to increasing demand for fresh yet convenient ready-to-eat foods (Klaiber et al. 2005; Lehto et al. 2014; Alarcón-Flores et al. 2014). In Canada, the farm-gate value of fruits and vegetable increased by 4% from 2014 to $1.9 billion in 2015, where Ontario accounted for 43% of all total vegetables grown in Canada (Statistics Canada 2016). This is largely due to the many health benefits of fruits and vegetables, such as preventing cardiovascular diseases and reducing the risk of certain cancers (Soerjomataram et al. 2010; Bhupathiraju and Tucker 2011; Stefler et al. 2016). Delivering fruits and vegetables to the consumers table requires large volumes of resources (water, nutrients and environment) and energy (input to grow, harvest and transport). For example, large facilities may use up to 100 m^3 of potable water per day for washing and processing needs (Casani et al. 2005).

Following harvest, produce is washed to remove soils, fertilizers and pesticides. Additional processing stages, such as cutting, peeling, sanitization and packaging, are added at some facilities. Water is also used for transporting product with in the facility and for in plant sanitization. The result is large volumes of potable waters are used, thereby generating equally large amounts of wastewater, typically referred to as wash-water (Casani et al. 2005; Hafez et al. 2007; Kato et al. 2013; Kern et al. 2006; Lehto et al. 2014, 2009; Mundi 2013; Mundi and Zytner 2015; Ölmez and Kretzschmar 2009). This wash-water may contain heavy loads of solids in the form of dissolved and particulate matter, high levels of organic matter and solids from peeling processes, elevated levels of chemical and biochemical oxygen demand (COD and BOD), nutrients (nitrogen & phosphorus) and pathogens. These water quality parameters normally exceed regulations set by Ministry of the Environment and Climate Change (MOECC), provincial and municipal governments, negatively impacting surrounding water courses, ecosystems and wastewater treatment plants. (Kern et al. 2006; Lehto et al. 2009 and 2014; Mundi 2013; Mundi and Zytner 2015). Based on the quality of wash-water, environmental regulations concerning wash-water treatment are becoming stringent all the time.

Wash-water refers to water used for washing fruits and vegetables. In the wash-water system, several batches of produce are often washed with the same water without any in-between treatment or have recharge rates that vary between 0 to 40% per/h (Salomonsson et al., 2014; Shortt, R & Nemeth, D., personal communication 2013-2016; Warriner et al. 2012). After its useful life, wash-waters are disposed of as wastewater. Wastewater from the fruit and vegetable washing and/or processing industry is often interchangeably referred to as wash-water instead of gray water, as it does not contain contaminants commonly found in domestic wastewater, such as feces and urine (Eriksson et al. 2002). As such, "wash-water" will be used herein when referring to wastewater from fruit and vegetable washing and/or processing.

Review of the literature shows that some work has been done on understanding the physical, chemical, and microbial qualities of wash-water and wastewater from different fruit and vegetable washing and processing operations (Casani et al. 2005; Hafez et al. 2007; Kato et al. 2013; Kern et al. 2006; Lehto et al. 2014, 2009; Ölmez and Kretzschmar 2009; Mundi 2013; Mundi and Zytner 2015). However, due to the large variation in values, growers still ask the question, what wash-water treatment process will work best for them. Best can be referred to a minimal treatment that allows discharge on their fields, to full treatment that allows recycling with minimal health risk. Given that soil washing and processing operations are highly variable due to soil and environmental conditions, along with changing crops, there is still limited information on the topic and datasets world-wide. As such, research efforts are needed to explore best management practices (BMP) for the treatment of wash-water with the potential for water reuse, which starts with investigating and characterizing wash-waters from different operations.

The first objective of this research was to characterize wash-water from different fruit and vegetable washing and/or processing facilities. Wash-water samples were collected from various fruit and vegetable facilities in southern Ontario and analyzed for typical water quality parameters. This allowed identification of trends and commonalities in the water quality parameters, understand removal efficiencies of current BMP for solids, nutrients (nitrogen and phosphorus), COD, BOD, and pathogens. The second objective of the study was to assess the effectiveness of various wastewater treatment technologies in reducing solids in raw wash-waters. Bench-scale experiments were conducted on all wash-waters to measure solids reduction efficiencies and the corresponding impact on the removal of secondary contaminants, such as COD, BOD, nitrogen, phosphorus, and pathogens.

Bench-scale testing consisted of screening (sieve), hydrocyclone, settling with coagulation and flocculation (C&F), centrifuge, dissolved air flotation (DAF) and electrocoagulation (EC). The primary focus was on the removal of solids. However, other water quality parameters were monitored for completeness. For ease of interpretation of results, averaged reduction values were converted to effectiveness ratings ranging from Poor, P (<40% removal), Satisfactory, S (40-60% removal), Good, G (61-75% removal), Very Good, VG (76-90% removal), to Excellent, E (>90% removal). Upon completing the analysis, decision matrices were developed to highlight treatment effectiveness for different fruits and vegetables according to the operation type (washing only vs. washing and processing) to provide the best quality water fit for the intended purpose. These decision matrices, which are considered rudimentary, address a deficiency in the literature as it will help producers and processor determine which technology they should consider to treat the wash-water they generate.

2 Background

Many treatment technologies exist to remove solids and other contaminants from wastewater like coagulation and flocculation, activated sludge treatment and sand filtration. However, when looking at the literature for specific examples in the agri-food industry, there are limited applications in the fresh-cut fruit and vegetable sector (Shortt, R. & Nemeth, D., personal communication, 2013-2016; Mundi 2013; Mundi and Zytner 2015). The generic systems that are available use a combination of physical, chemical and biological methods, although most are costly and difficult to maintain. In any case, many are beyond the requirements of fresh produce processors. Increasing stringent standards along with water costs have increased the need for on-site wastewater treatment. Compounding the problem is that most of these facilities try to limit the budget on treatment processes. By understanding the behavior of bench-scale treatments with different wash-water types (washing and/or processing), one can determine the effectiveness of treatments, allowing for implementation of BMPs. The level of treatment and removal of constituents will dictate the end use of the treated waters.

In total, six different water treatment systems were explored after discussions with Ontario Ministry of Agriculture, Food, and Rural Affairs (OMAFRA) regarding what growers typically adopt as generally cost-effective, easily implemented and effective in reducing solids. The six processes are screening (sieve), hydrocyclone, centrifuge, settling with coagulation and flocculation, flotation, and electro-coagulation.

2.1 Screening (Sieve)

Screening is the first step in treating any wash-water as it removes large objects and particles from the wash-water stream that are generated due to washing and processing of fruits and vegetables (Ljunggren 2006; Valta et al. 2015). Screening can be done with a course and/or fine mesh (200-50 μm) to retain large particles (Lee 2007). Screening is an elementary, simple, and cost-effective step in treating any wastewater, but requires additional investigation to identify when it works best for agri-food wash-waters (Ljunggren 2006).

2.2 Hydrocyclone

Unlike screening or sieve, a hydrocyclone does not have a physical separator. Instead, a vortex is created via a pressure differential inside the hydrocyclone allowing heavy solids such as sand/silt to be ejected at the underflow of hydrocyclone. Hydrocyclones have been used in many applications of solid-liquid and liquid-liquid separation (oil and water) (Son et al. 2016). Its simplicity of operation, lack of moving parts (other than the pump) and low maintenance costs make it advantageous to use in small-scale operations or low-technology processing, where it can easily be fitted to an existing pump (Bain and Morgan 1983; Hwang et al. 2012; Soccol and Botrel 2004; Yang et al. 2013). Literature review did not show any commercial applications specific to fresh produce washing/processing. However, hydrocyclones have been conventionally used for potato starch separation, grit removal from wastewaters, and in the wet milling industry for starch-protein separation (Verberne 1997; Mansour-Geoffrion et al. 2010; Singh and Eckhoff 1995).

2.3 Centrifuge

Another form of mechanical solid-liquid separation method is centrifugation. The high spin rate separates the particles from the water. Various types of centrifuges are available for sedimentation and filtration as applications exist in all types of industries. Recent developments of centrifugation technology are highlighted by Anlauf (2007). For this study, the focus will be on sedimentation type centrifuges, where high-speed rotation forces are used to separate solids from liquid in a rotating cylindrical bowl (USEPA 2000). Centrifuges have been used for many decades to dewater or thicken solids from anaerobic digestion for subsequent composting or landfilling (Park et al. 2011). Sometime polymers are added to improve separation efficiencies. Dewatering also reduces the volume of solids waste, which affects transportation costs for disposal or possible use as a by-product (e.g., cattle feed). High solid reduction efficiencies and small footprint design allows for use in multiple applications and is often preferred when dewatering solids (Norton and Wilkie 2004).

2.4 Coagulation and Flocculation Process (C&F)

C&F is widely used in the wastewater and food industry to precipitate out particulate and dissolved matter (Hafez et al. 2007; Van Haute et al. 2015). The three types of coagulants commonly used in C&F are metal salts (alum or ferric sulfate), polyelectrolytes (polymers) which are effective but expensive, and natural (chitosan) (Renault et al. 2009; Ahmad et al. 2004). C&F

works on the principle of neutralizing the wash-water particles that are negatively charged, which causes destabilization of repulsive forces and permits flocculation, agglomeration and formation of particles. C&F works best for solids with a specific gravity greater than water to remove the particles (Van Haute et al. 2015; Miranda et al. 2013; Sahu and Chaudhari 2013). However, there are challenges when the specific gravity is close to 1, like carrot peels (Mundi and Zytner 2015).

2.5 Sedimentation (Settling)

Settling can provide effective means of reducing solids content. It may also be used as a pre-treatment for DAF system or membrane filtration (Valta et al. 2015; Khiadani et al. 2014). Many different types of settling tanks and configuration are available on the market, including inclined (plate and tube) settlers (USEPA 1999). Most applications make the use of settling ponds or long rectangular settling tanks, due to cost and treatment effectiveness. Conventional settling treatment methods occupy a large footprint, however this can be overcome by inclined plate settlers (Gregory and Edzwald 2011; USEPA 1999). The plate settlers increase the area available for settling thus increasing the discrete settling of particles. Sedimentation is essential for grit removal and larger particulate matter and can be one of the most cost effective treatments methods to date (Kern et al. 2006). Combined with the C&F process, settling can provide high quality treated waters.

2.6 Dissolved Air Flotation (DAF)

Flotation is a clarification process with the simple principle of causing the solid particles in the wastewater to rise to the top of a flotation tank with the aid of fine air bubbles that are produced at the inlet of the flotation tank. Compressed air is the main agent of use for flotation. DAF is very good at removing low density material that may not settle easily. C&F principles can also be used for DAF as they serve to destabilize particles present in the wash-water and most importantly to convert dissolved organic matter into particulate matter (Gregory and Edzwald 2011). Optimum coagulation conditions are necessary for efficient removal of particles as is the case in sedimentation. Both Teixeira and Rosa (2007) and Han and Kim (2000) have shown C&F with DAF to be superior when compared to C&F with Settling due to DAF's ability to remove cryptosporidium and algae. Mundi and Zytner (2015) showed that DAF was an effective technology for removing carrot peelings from wash-water.

2.7 Electrocoagulation (EC)

Electrocoagulation is an emerging technique being utilized by agro-industry wastewater, including food industry (Drogui et al. 2008; Kabdaşlı et al. 2012; Qasim and Mane 2013). Electrocoagulation applies an electoral current to the wastewater through aluminum or iron electrodes, which destabilizes the negative charge as done in coagulation, and allows for the flocculation of particles. More specifically, the electrodes are sacrificial and generate aluminum hydroxide ($Al(OH)_3$). The generation of hydrogen causes the floc to float. This technology possesses many advantages such as in situ coagulation (minimal chemical use), easy installation, odour & colour removal, lower secondary pollutions, ability to reduce microorganism loadings, and most importantly low residence times (Chopra 2011; Drogui et al. 2008).

3 Methods and Materials

The study was conducted in southern Ontario, Canada. Samples were collected from 14 facilities processing various types of fruits and vegetables as noted in Table 1. The samples were collected post processing and at various locations within the processing stream, including soil washing, cutting and/or peeling. Some facilities also had on-site treatment systems, so pre- and post-treatment samples were also collected. Table 1 provides clarification on the different type and number of samples collected at each facility, type of product washed or processed, and facility codes, which will be used here on. As such, the number of samples for each facility varied from 2 to 16, giving a total of 83 samples collected. The 83 samples also had duplicates, where each sample was characterized by 20 different analyses resulting in a total of 26 water quality parameters for a total of approximately 3,000 (83x2x20) data points. For facility C1 and MV2, the samples were not assessed for all 20 water quality parameters due to changes in the lab procedures. For all 14 facilities, raw wash-water samples were subjected to six bench-scale treatments as noted in Section 2, which were also characterized for the suite of water quality parameters, generating approximately 19,000 (83x2x20x6) data points.

Approximately 2 litres (L) of sample was collected at each sampling point for determining water quality parameters. The samples were tested immediately upon return to the lab or within 24 hours. Treatment testing required about 40 L of wash-water from each sampling point per sampling visit. When possible, fresh wash-water was used during bench-scale treatment testing. For additional testing, wash-waters were stored in laboratory refrigerator, set at 4 °C until use for testing.

3.1 Wash-Water Characterization and Bench-scale Testing

All wash-waters were analyzed before and after treatment, when possible, for typical water quality parameters. See Figure 1 for process flow diagram of the study. Table 2 shows the water quality parameters that highlight the physical, chemical, biological and microbiological properties of the wash-water. Table 2 also shows abbreviated names of water quality parameters which will be used from hereon, i.e., TS for total solids. All samples were tested based on the procedures listed in the Standard Methods for Examination of Water and Wastewater, 22nd Edition (Rice et al. 2012).

Statistical summaries were computed on collected water quality parameters such as averages, median, standard deviation, minimum and maximum values for the different categories of wash-waters. The raw water quality parameters of wash-water and the corresponding treatments (Jar test, DAF, etc.) will be compared in terms of reduction efficiencies. Reduction efficiency is represented by formula, $((C_i-C_f)/Ci) * 100$, where C_i is the initial concentration and C_f is the final concentration. These reduction efficiencies allow the calculation of reduction achieved in each water quality parameters for the different treatments to better understand solids reduction.

For bench-scale testing, the equipment and approach was based on current methods used in the industry. Screening was assessed through batch tests, by pouring 500 mL of wash-water sample onto a standard soil sieve of 100 µm size, placed on top of a 1 L glass beaker. Clarified samples were assed for appropriate parameters. The test was used to understand the reduction in solids from screening of wash-waters. The hydrocyclone experiment used approximately 4 L of well mixed wash-water sample pumped at a flowrate of 1.3 L/min to a 48 mm diameter of acrylic polymer 3-D printed hydrocyclone. The apex and vortex finder of the hydrocyclone were 4 and 6.7 mm in diameter, respectively.

Centrifugation was done using a GS-6R Centrifuge (Gh-3.7 Horizontal Rotor). The test procedure consisted of using two 250 mL centrifuge bottles for per wash-water sample at 1801 x G (3,500 rpm) for 3 minutes. Both bottles were weighed and corrected to have equal mass to ensure balanced operation of the centrifuge machine. The clarified samples were decanted from the top and assessed for water quality parameters.

Coagulation-flocculation-sedimentation experiments were conducted with a jar test apparatus from Phipps & Bird Stirrer, Model 7790-400. Six jars were filled with 500 mL sample of wash-water each, five of which were dosed with coagulant ranging in concentration (1-400 mg/L) of prepared coagulant mix, with the 6th jar as the control. The wash-water was stirred for 1 min at 100 rpm for rapid mixing to dissolve the added coagulant and 10 min at 30 rpm for slow mixing to allow flocculation of particles. The formed flocs settled for 20 min after which the upper 100 mL were decanted from the jar using a pipette and analyzed for turbidity. The same experiment was executed a total of four times to assess the four types of coagulants as noted below. The coagulant type and dosage yielding the best result as measured by turbidity was repeated using 1 L wash-water sample to produce 400 mL of decanted sample for water quality analysis.

The four coagulants explored in this study consisted of Nalco ULTRION 8187 (Aluminum Chloride Hydroxide), Chitosan (polysaccharide from shrimp shells), Sigma-Aldrich (Poly(diallyldimethylammonium chloride)), and Polyglu (polymer of the amino acid glutamic acid - Water Treatment Agent PGα21Ca). FeCl and Alum coagulants were only explored on C1 facility's wash-waters as the performance was poor.

The DAF systems composed of two custom built graduated cylinders, which acted as the reaction chambers and a pressure vessel for providing air-water mixture. Tap water was pressurized to 70 psi in 10 L vessel for 10 minutes and a 50% recycle rate was used on 1L wash-water sample held for 10 minutes. The recycle rate refers to the volume of water under pressure, held in the 10 L vessel that will be released to the reaction chamber to cause flotation. After which the samples were extracted from middle of the graduated cylinder and assessed for water quality parameters.

Electrocoagulation bench scale experiments were performed with two different setups. Initially a small version of the experiment was conducted in a 100mL reactor, which was later improved to 500mL reactor to process larger volume of clarified sample. Both setups consisted of utilizing aluminum electrodes or plates (second setup) in a reactor (beaker) to allow the wash-water sample to be charged with DC current. The range of voltages and currents were set using a Solartron Impedance-phase Analyzer. The reaction surface areas were 1.571 and 575.1 cm^2 with current densities of 54 and 0.35 A/m^2 for the small and big experiment setups, respectively. Considering the reactor volume, the reaction time of 30 and 10 mins, the corresponding power consumption is 6.8 and 0.27 KWh/m^3 of treated waters. Since aluminum electrodes are used for the reaction, the electrode dissolution rates were determined to be 0.14 and 0.022 kg/m3 for the small and the large setup, respectively. Upon completion of the experiment, the clarified water was decanted and analysed for water quality parameters.

4 Results and Discussion

4.1 Characterization

Wash-water samples were collected from different fruit and vegetable producers and processors in southern Ontario from 2013 - 2015 to better understand and document water quality parameters, and thereby to assess water treatment options. Overall, the characterization and lab scale treatment testing generated a large data set of about 8,000 samples. Facility codes and operating parameters are provided in Table 1.

Wash-waters from the sampled facilities were grouped into four main categories: tree fruit (apple), leafy greens (spinach), root vegetables (root crop; carrots, potatoes, sweet potatoes, ginseng), and mixed (vegetables grown above ground, root crops, leafy greens and tree fruits). Ranges of water quality parameters encountered in these categories of wash-waters are highlighted in Table 2. Levels of solids, BOD, nutrients (TN&TP), and pathogens may be predicted from the category of wash-water. Each facility required some or all of the three stages for washing and processing of vegetables and fruits, washing (removal of soil), processing (budding, cutting & peeling), and packaging (cooling and disinfection). Thus, each facility will be classified according to the general operations it uses: washing (W) or washing and processing (WP), as indicated in Table 1.

Water quality parameters of tree fruit wash-waters were highly variable as shown in Table 2. The lower values in all categories were due to washing only, while higher values were a result of facilities with juicing lines in addition to washing apples. Similarly, root crops also show high variability in water quality parameters due to facilities both washing and/or processing (cutting/peeling) fruits and vegetables. Leafy greens and mixed wash-waters had the lowest variability in all categories.

Review of Table 2 shows that root crops have high levels of SS, while tree fruit, leafy greens and mixed wash-waters were higher in DS. SS are much easier to treat as they settle out faster in settling ponds/tanks compared to DS. TS are generally higher for root crops due to soils, loose root materials, or wasted products that do not meet quality standards. Float materials were also common in root crop wash-waters. One example is ginseng wash-waters, which contain materials consisting of root hairs. Water flow rates used for washing can also impact level of TS encountered in wash-waters from different facilities. Low water flow rates (water management) lead to higher level of solids in wash-water, as a result producing a concentrated stream, while higher water flow rates require greater volume of wash-waters to be treated for disposal or reuse. TS levels directly impact other water quality parameters such as COD, BOD, TN, TP and pathogens.

COD and BOD were relatively low for leafy greens and tree fruit when compared to root crops and mixed wash-waters. Processing (juicing, peeling, and cutting) produced higher levels of COD and BOD due to the release of fine and dissolved organic matter into the wash-water. High levels of TP exist in wash-waters from tree fruit in comparison to root crops, which were higher in TN levels. The high levels of TP encountered in tree fruit washing is a direct result of 5-day water change cycles for dunk tanks. While, levels of TN and TP were moderate in mixed and quite low in leafy greens wash-waters. The high levels of TP and TN seen in root crops are due to recirculation of wash-water for washing. These practices are utilized in the fruit and vegetable washing industry to reduce water usage for washing and process needs. Fecal indicators such as

E.Coli were below detection limit for tree fruit (washing) and leafy greens wash-waters, while root crops, mixed and tree fruit (juicing) had detectable levels.

In general, characteristic assessment of fruit and vegetable wash-waters showed that solids are generated by many factors, such as soils and peels. However, DS are contributed by leafy greens and tree fruit washing and processing wash-waters, i.e., for LG1, A1 and A2. High levels of SS are encounter in wash-waters from soil washing only, i.e., for G1, G2, P1, P2, SP1 and SP2, some of the root crops. The values listed in Table 2 show these trends. BOD and COD levels from washing are minimal in comparison to both washing and processing operations. It seems that soil wash-water contributes equally to the generation of TN and TP, unless it is from root vegetables. While washing and processing wash-waters contribute higher loads to TN as compared to TP.

4.2 On-site Treatment

Some facilities have on-site treatment systems to handle wash-water while others have access to municipal sewers. On-site treatments systems can be categorized into four types: I) single settling tank/pond, II) three settling tanks/ponds in series, III) four stage sequential reactors (settling, aeration, nutrient removal, settling), and IV) advanced treatment, which composed of membrane bioreactor (MBR), reverse osmosis (RO), and ultraviolet disinfection(UV). Performance of the on-site treatment systems are highlighted in Table 3.

At first glance, it was noticed that some related parameters have different removal rates. This is seen for SS and turbidity, which are not always in agreement, as seen in Table 3, facilities G1-Grasslands, G2, MV1, P1 and P2. This is due to the inherent difference in the measurement method. Turbidity measures the scattering effect particles have on light, while SS is a weighted method of measuring particles in water. The scattering of light is a function of type, size, shape and concentration of particles. Thus, SS and turbidity are not always correlated. Differences in BOD and COD values may be due to COD test's ability to measure oxidation of inorganic chemicals in addition to decomposition of organic matter, the latter being measured by BOD (Patil et al. 2012). Wash-water characteristics can vary in nature, such as in percentage of organic and inorganic matter, dissolved and suspended matter.

Assessment of on-site treatment systems, as highlighted in Table 3, revealed a range of feasible options for disposal and reuse of treated wash-waters. Wash-waters containing high levels of TS and SS utilized settling tanks and ponds to reduce solids. Some producers employed a series of settling tanks to reduce solids as effectively as possible. The introduction of air into settling ponds (biological treatments) led to a reduction of TP and TN along with BOD and COD. Current water reuse applications vary from recycling water from settling tanks to post biological treatment with fresh water blending. However, only the advanced treatment process, observed at facility A2, was capable of treating waters to drinking water standards, providing unlimited applications for water reuse.

4.3 Bench-Scale Treatment Assessments

Focus of the study was to test the effectiveness of various treatments in reducing the solids content of raw wash-waters as this was the initial concern of OMAFRA. The bench-scale treatments were conducted for all wash-waters to better understand reduction efficiencies of solids, and the corresponding impact on the removal of nutrients (N&P), BOD, COD, and pathogens. The samples tested were averaged to provide average reduction efficiency values, which are then converted to effectiveness ratings for ease in understanding treatment trends.

The coefficient of variation (CV) was used to compare variability between different measurements within water quality testing procedures and bench scale treatment testing procedures. Lower values of CV mean lower variability in testing, which is important to highlight reproducibility of testing and experiments. For water quality testing procedures, CV of 10% or less was achieved for absorbance, transmittance, turbidity, COD, BOD, and conductivity. Low CV is a result of using instruments with rapid measurements, such as turbidity meter, which give fast and accurate measurements. While TS, SS, TP, TN, and Ammonia were below 18%, which could be due to methodologic error as they require many steps where human error is also easily introduced. CV for water quality parameters testing indicate high reproducibility and confidence in measurements.

Similarly, confidence in bench scale treatments can be assured, as CV for all treatments were 29% or less. Screening and centrifuge were highly reproducible with a CV of 8% or less, while CV values for hydrocyclone, settling, and settling with C&F ranged from 10 to 17%. DAF and EC had CV values of 26 and 29%, respectively, which were to be expected. DAF experiment consisted of many control parameters, such as pressure, water detention rate under pressure, wash-water retention rate in flotation cylinder, and recycle rate. While, EC experiment encountered problem of re-mixing of solids with clarified waters, which could also have contributed to CV along with inherent human errors. CV analysis highlights no significant errors in the reproducibility of water quality testing and bench scale experiments, thus assuring confidence in study results.

The reduction efficiencies were converted to effectiveness ratings. Like a grade system utilized in the education and wastewater sector, the ranges of reduction efficiency corresponding to effectiveness rating were decided upon arbitrarily. These ratings were discussed with colleagues at OMAFRA, who agreed that these ranges would be understood by the user since similar ranges have been used in literature. The ratings are as follows: Poor, P (<40% removal), Satisfactory, S (40-60% removal), Good, G (61-75% removal), Very Good, VG (76-90% removal), Excellent, E (>90% removal).

Ratings for each bench-scale treatment are presented in Tables 4 through 10. For some treatments (screening, hydrocyclone, and settling), fewer water quality parameters were measured due to operational issues in the laboratory. The limited parameters covered essential water quality parameters, such as turbidity, absorbance, and transmittance, which are adequate to assess solids reduction effectively. These are particularly useful when TSS or SS were not available due to their rapid measurement methods, as the case in settling experiment. The primary focus of the study was to assess reduction in solids from different treatments. Removal of solids also impacts other wash-water properties, such as reductions in TN, TP, COD, BOD, pathogens, and other parameters, known as secondary parameters. So, it was important to record the effect on secondary parameters for treatments which have the potential to allow water reuse, such as C&F, DAF, and electrocoagulation technology.

4.3.1 Screening

Lab scale testing showed that screening (sieve) treatment was most effective on wash-water from washing that contained heavy levels of sand and large peels (facility SP2 & G2), followed by other root-vegetables being washed only (facility G1, P2 & SP1), as seen in Table 4. Results varied between operation types, with process washing vegetables having heavy soils (SP2 & G2) or utilizing low flow waters (G2) could benefit from the use of screening. Effectiveness in screening varied for washing and peeling facilities; MV1 and C2 showed poor reduction while P3 had good reduction in turbidity. The least effective were A2 and LG1 wash-water as they contained larger proportions of dissolved solids. Overall, screening treatment was effective on wash-water containing heavy loads of sand, large peel pieces or other larger organics. It was ineffective for wash-water containing dissolved materials (leafy greens and apple washing).

4.3.2 Hydrocyclone

Hydrocyclone testing worked well with high levels of solids containing sand, but poorly with other types of wash-waters. As seen in Table 5, facility G2, SP2 and MV1 had very good to excellent SS, DS, and TS reductions showing the promise of using hydrocyclone treatment. In addition, facility P2 and P3, which also contain heavy soils showed good reduction in turbidity, this is due to reduction in solids leading to a change in turbidity. It is important to note that hydrocyclone was effective for most root vegetables other than C2, G1 and P1. Facility C2 washes and processes carrots grown in muck soils, which can be difficult to settle out using gravitational forces, as the muck soils contain very high levels of organic matter unlike mineral soils. Facility G1 washed ginseng, which naturally contained float materials from roots and are not suitable for hydrocyclones.

4.3.3 Centrifuge

The centrifuge functions similarly to the hydrocyclone, but the much higher gravitational forces making it easier to remove particles of larger mass. For this reason, it effectively reduced solids in all facilities, as indicated by the high reduction in turbidity and SS, apart from facility A2, which had very high levels of DS, as seen in Table 6. TS reduction ranged from excellent to good (E to G) for most facilities that wash root-vegetables (G1, G2, P1, P2 & SP2), but satisfactory to poor (S to P) for nearly all washing and processing operations (A1, A2, LG1, C2, MV1 & P3). BOD and COD reduction varied, but seemed to be least reduced for A2 and LG1. Between TN and TP, TP had higher reduction in comparison to TN. This may suggest that the removed TP was contained within the suspended solids, which are easily removed by centrifugation. Overall treatment impact on water quality parameters varied, but both SS and DS were reduced effectively.

4.3.4 Settling

Settling treatment processes allow large solid particles to settle out at the bottom of the pond or tank through gravitational forces. Natural settling is a cost-effective solution to reducing solids from washing and processing wash-waters. Table 7 highlights the results from settling experiments composing of "control" jars only, meaning no coagulant were used for these jars, thus highlighting the natural capabilities of wash-waters to settle out particles. Settling was least effective for A2, G2, P2 and P3, which are mostly composed of root-vegetables and processing wash-waters, with high levels of dissolved solids from peels and soils. The dunk tank utilized at facility P2 allows for build-up of soils, leading to high levels in TS and SS. Washing and peeling at

P3 led to wash-waters with high amounts of fine soils and dispersed organic materials making it challenging for particles to settle.

Facility G2 and P2 require much higher settling times to improve settling efficiency as their wash-waters contained high levels of SS materials. Root vegetable washing and processing wash-waters at facility C2 and MV1, and washing wash-waters at facility P1, SP1, A1 and LG1 show poor to moderate reduction efficiencies. This is a result of these facilities handling root-vegetables, which generally have heavy loads of soils and peels, making it difficult to reduce all solids with just one treatment step. For the tree fruit and leafy greens, which consist mainly of DS, it is difficult to settle out the solids without the use of coagulants. Overall, wash-water with high levels soils and DS are not effective under settling, such as A2, G2, P2 & P3.

4.3.5 Settling with C&F

Settling with C&F was explored to understand improvements in the removal efficiencies of different water quality parameters using chemical aids. All wash-waters for settling with C&F achieved an excellent to very good reduction for solids, as indicated by turbidity and SS, but dissolved solids were marginally affected as seen in Table 8, which is consistent for coagulation and flocculation. COD reduction ranged from excellent to very good for all wash-waters, except for A2, LG1, and P3. TP had higher reduction compared to TN, expect for LG1 where, both TN and TP were poor. Ammonia and TN were both poor for potato wash-waters.

The applied dosages for jar testing ranged from 5 to 600 mg/L for Nalco, Chitosan, Polyglu, and Sigma, while metal based precipitation chemicals, such as Alum and FeCl were much higher at 250 – 10,000 mg/L. Jar testing results demonstrated that optimal dosages need to be in the range of 5 to 250 mg/L for Nalco, Chitosan, Polyglu, and Sigma coagulants, as shown in Table 8. These are much lower dosages in comparison to Alum and FeCl dosages, as they are polymer type coagulants versus conventional metal based coagulants. Polymer coagulants have the advantage of not being dependant on pH and attracting both inorganic and organic particles. Alum and FeCl doses ranged from 250 to 5,000 mg/L, where low pH wash-waters (approximately 4) were responsible for low dosages leading to 80% and greater reduction in turbidity (Mundi 2013; Mundi and Zytner 2015). Although detailed jar testing results exist, only a summary was provided to highlight the potential use of different types of coagulants to enhance settling treatment. The summary also demonstrates the variability encountered within wash-water samples and facility, due to several variable operating conditions. Detailed results show variability exists among samples tested under the same coagulant because raw wash-waters have varying properties. These dosages are in line with literature findings on wash-water from root vegetables and leafy greens, which are also very limited (Hafez et al. 2007, Van Haute et al. 2015).

Producers and processors must be aware of optimum coagulant dosages and types (Nalco, Chitosan, Polyglu, Sigma), to optimize treatment system and reduce costs. Compounding the problem are the different wash-waters that are generated throughout the season due to variability in produce coming in or production requirements (processing vs. washing). All four coagulants demonstrated optimum dosages for one type of wash-water or another, highlighting the availability of precipitation chemicals for settling based treatments. Understanding dosage requirements for wash-water allows for a better cost estimate of coagulant use. Further reduction of costs can be achieved by utilizing primary grit chambers. Use of coagulants will help achieve the best treated waters, however dosage and cost must be considered.

4.3.6 Dissolved Air Flotation

DAF treatment showed promising results as seen in Table 9. DAF was able to reduce COD more effectively than settling and C&F combined with settling, while also reducing solids and nutrients. This is consistent with DAF be most effective with particles having a light specific gravity. Solids reduction was particularly good for wash-waters with high levels of DS (A2, C2, P3, MV1). These are facility with both washing and processing stages. COD seemed to be well reduced for all wash-waters due the addition of oxygen via the air bubbles, except for A2, LG1 and P3, which all have intense processing operations and high levels of dissolved solids. Nutrients were also reduced effectively as TP had a higher reduction rate when compared to TN. The added oxygen provided for better reduction of nutrients when compared to settling with C&F. Treatment worked well on most wash-waters except for wash-water involving processing (A2, LG1, MV1, P3).

4.3.7 Electrocoagulation

EC provides very high levels of treatment as the electrical charge ensures effective COD, BOD, and pathogen reduction, in addition to providing C&F effect for solids reduction. It is true that EC is effective at removing solids/colloidal matter, however the cause of reduction in pathogen levels (electro-oxidation effect) cannot be confirmed. It is unclear whether the reduction is due to solids or oxidation effect, but a reduction none the less, which is of great interest. Table 10 shows that EC was highly effective on SP2 and G2, wash-waters that had very high levels of soils. More testing is needed with electro-coagulation, as only limited number of samples were tested. Most wash-waters had a good reduction in all parameters, except for A2, which was due to the heavy loading of solids as seen in the raw wash-waters of facility A2. Facility C1 and LG1 did not show significant reduction in COD and nutrients reductions. Producers that reuse/recycle/recirculate wash-water (A2, G1, C2 and P1) and those using dunk tanks have high dissolved solids (LG1 and SP1), leading to low effectiveness of EC treatment. For improved efficiencies, EC reaction time can be increased or pre-treatment can be introduced. Also, the use of post-treatment such as membrane filtration may be needed to remove dissolved constituents.

4.4 Treatment Decision Matrices

The goal of this study was to understand the impact of various treatments on wash-waters from different fruit and vegetable types (root vegetables, leafy greens and fruit) and operation types (washing or washing and processing). Additionally, water reuse potential was addressed as it is important to minimize overall water demand when washing and processing vegetables and fruits. Thus, four decision tables to represent the reduction in solids, COD, TN & TP, and E.Coli were developed to highlight the effectiveness of each treatment on wash-waters and operation types. Tables 11, 12, 13 and 14 are the decision tables that present the treatment effectiveness of various bench-scale treatments on wash-waters presented in this study, according to the operation type (washing – W or washing and processing – WP).

Treatment effectiveness for solids reduction is highlighted in Table 11. It is important to remove solids from wash-waters whether the end goal is reuse or disposal. The recirculation of wash-waters leads to a buildup of solids, resulting in higher amounts of pathogens as well as a higher oxygen demand, among other things (Selma et al. 2008a, 2008b; Van Haute et al. 2013, 2015). Thus, it is vital to decrease solids that can be easily reduced via screening and hydrocyclone given the simplicity and cost effectiveness of these treatments.

Natural settling processes can be quite effective under optimal conditions, but the volumes of water used in the fruit and vegetable industry are large, leading to short residence times. Bench-scale settling showed good to poor performances, highlighting the need for optimizing the settling processes. Thus, C&F with settling was the most effective, given the use of chemical aid. C&F with settling was the most effective method for rapid treatment and wash-water reuse, followed by EC, DAF, Centrifuge, Settling (natural), HC, and Screening, in that order.

Table 12 highlights COD reduction, signifying which treatments can provide the most effective reduction in oxygen demand. EC treatment was the most effective due to electro-oxidation capability, followed by C&F, DAF and Centrifuge. High COD values combined with high dissolved solids levels, as encountered at facility LG1 and A2, show poor improvements with all bench-scale treatments and produce (apple WP, leafy greens WP, & potato WP). This makes it challenging to reduce COD effectively regardless of treatment technology employed. Biological treatments utilizing aeration or advanced MBR processes combined with membrane filtration may be the only option wash-waters having elevated COD values like LG1 and A2.

Table 13 presents results for TN and TP reductions. In general, TP was reduced more effectively in comparison to TN using C&F with settling and DAF (both used chemical coagulants). In contrast, TN and TP were reduced proportionally using centrifuge treatment. It was evident from Table 13 that mixed vegetable, leafy greens, and apple wash-waters had low reductions in TN compared to TP. In conclusion, both C&F with settling and DAF are a viable method to reduce TN and TP in wash-waters, due to use of chemicals. Table 14, highlights pathogen reduction, which was surprisingly high yet plausible since most bench-scale treatments could reduce high levels of SS. As SS have the potential to trap and hide a significant number of pathogens.

Developing the decision matrices provided in Tables 11 to 14 is considered Phase 1 of the study as the matrices provide a simple way of approximating which treatment technology should be selected based on the produce and type of wash-water generated. Based on the success of Phase 1, the work continues under Phase 2 of the study which involves creating a statistical model that predicts the most effective treatment option for a particular wash-water type and given specific inputs, such as water quality parameters and operation types. The statistical model will promote more evidence-based decisions surrounding the selection of a feasible treatment system. The results of Phase 2 will lead then into Phase 3 of the study which uses neural network analysis to develop a predictive model for wash-water treatment options.

5 Summary

Wash-waters generated in the agri-food sector in the processing of fruit and vegetable produce are diverse in water quality parameters as they vary not only across different fruits and vegetables (sector and industry) but also within a particular produce (product) and operation type (facility). The wash-water generated has high variability in water quality parameters, such as solids, COD, BOD, TN, TP, and pathogens. This variability makes it challenging to implement a standard treatment option. As a result, the fruit and vegetable industry utilizes many treatment options to dispose or reuse wash-waters, ranging from simple settling ponds/tanks to MBR systems. Drinking water standards for water recycling are also met by augmenting (dilution) fresh water with treated wash-waters.

The completed research generated many data points from the sampling of various producer facilities for a variety of fruit and vegetable produce. The sampled wash-water was tested in various bench-scale treatments to determine how effective these treatments were in removing standard water quality concerns like solids, nutrients and organic matter. Analyzing the data allowed the development of treatment decision matrices, which can help producers select the ideal treatment technology for their produce; initially to implement pilot scale, followed by full scale wash-water treatment. The treatment decision matrices also showed the potential for water reuse given the high level of solids and related water quality parameters reduction by some treatments, i.e., C&F with settling and electrocoagulation. The decision matrices along with compiled information on wash-water characterization and on-site treatments provide growers, government, and consultants with information on determining treatment options that were not previously available or studied in literature.

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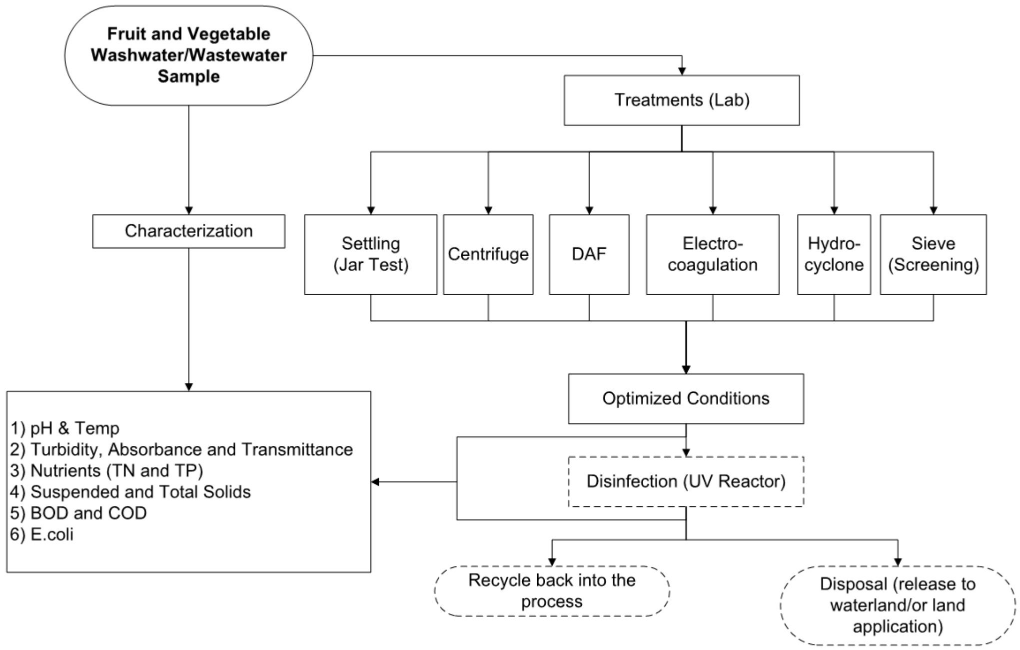

Figure 1: Process Flow Diagram of Wash-water Bench-scale Treatment Testing

Table 1: Vegetable and Fruit Washing and Processors Wash-water Information.

FACILITY	TYPE OF PRODUCE	OPERATION TYPES*	WATER USAGE AND OPERATION LENGTH	TREATMENT TYPE AND VOLUME (m^3)	SAMPLES (# COLLECTED)
A1	Apple	W	NA	Sand Filtration	**A1F1 (1), A1F2 (1), and A1F3 (1); N=3
A2	Apple	WP (Juicing)	10 m^3/hr; All year	Biological MBR with RO and UV	Pre and post treatment; N=4
C1	Carrot	WP (Peeling)	14 m^3/hr; Half year	Settling Pond	Multiple samples along processing line, pre and post treatment; N= 16
C2	Carrot	WP (Peeling)	114 m^3/hr; Half year	Settling Tank – 543 m^3	Pre and post treatment; N=6
G1	Ginseng	W	15 m^3/hr for 10hr/day and 1 week/yr	Settling Tank – 6.5 m^3	Pre and post treatment; N=4
G2	Ginseng	W	1.4 m^3/hr for 9hr/day and 12 days/yr	Settling Tank 1.8 m^3	Pre and post treatment; N=4
LG1	Spinach	W	NA; All year	Effluent to Municipal Sewer	Raw wash-waters; N=3
MV1	Root vegetables	WP	NA	Series of 3 settling tanks/ponds	Raw wash-waters; N=6
MV2	Vegetable grown above ground, root vegetables, leafy greens and apple	WP (Peeling)	15 m^3/hr; All year	Sieve, settling tank, followed by effluent release to Municipal Sewer	Raw wash-waters; N=12
P1	Potato	W	1.7 m^3/hr; Half year	4 Cell SBR – Each cell 100 m^3	Pre and post treatment; N=6
P2	Potato	W	2.8 m^3/hr; NA	3 Settling ponds (settling-aeration-settling) – Each about 250 m^3, followed by 2 wetlands – Each 80 m^3	Pre and post treatment; N=5
P3	Potato	WP (Peeling)	NA	3 Settling tanks - (1) 1.5 m^3 (2) 10 m^3 (3) 1 m^3	Pre and post treatment; N=6
SP1	Sweet Potato	W	NA	Settling tank - 6. 7 m^3 followed by settling pond – 34 m^3	Pre and post treatment; N=6
SP2	Sweet Potato	W	NA	NA	Pre and post treatment; N=2

* W – WASHING; WP – WASHING AND PROCESSING
**A1F1 – APPLE 1 FLUME 1, A1F2 – APPLE 1 FLUME 2, AND A1F3 – APPLE 1 FLUME 3

Table 2: Range of Raw Wash-water Quality Parameters of Tree Fruit, Root Crops, Leafy Greens and Mixed Categories between washing (W) versus washing and processing (WP)

Number of Samples	5	39	3	9
Facility	Tree Fruit	Root Crops	Leafy Greens	Mixed
Product	Apple	Ginseng, Potato, Sweet Potato, and Carrot	Spinach	Root crops, tree fruit, and leafy greens
Operation Type - Washing (W) or Washing and Processing (WP)	W – WP	W – WP	WP	WP
Statistics	Range Min(W) – Max(WP); Median	Range Min(W) – Max(WP); Median	Range Min – Max; Median	Range Min – Max; Median
pH	6.0 – 10.4; 6.4	6.6 – 7.8; 7.3	4.3 – 4.6; 4.6	7.0 – 7.7; 7.6
Temperature	12 – 28; 13	4 – 23; 17	17 – 21; 19	5 – 22; 11
Turbidity (NTU)	4 – 82; 23	86 – 1000***; 745	61 – 110; 66	104 – 590; 530
Transmittance (%)	0.5 – 88.2; 70.5	0.1 – 53.4; 0.1	18.5 – 51.4; 40.8	0.8 – 22.0; 1.1
Total Solids (TS) (mg/L)	575 – 8,860; 800	575 – 13,850**; 2,130	575 – 640; 525	305 – 1,970; 930
Suspended Solids (SS) (mg/L)	43 – 140; 100	182 – 12,730**; 1,770	30 – 215; 70	290 – 650; 455
Dissolved Solids (DS) (mg/L)	444 – 8,740; 660	364 – 1,810**; 925	398 – 496; 425	675 – 1,370; 650
Chemical Oxygen Demand (COD) (mg/L)	20 – 3,900; 140	110 – 12,100; 820	50 – 580; 290	105 – 170; 165
Biochemical Oxygen Demand, 5-day (BOD5) (mg/L)	10 – 2,280; 25	10 – 3,760; 65	154 – 620; 215	10 - 1,830; 50
Total Organic Carbon (TOC) (mg/l)	7 – 1,330; 18	12 – 135; 102	83 – 183; 130	26 – 28; 27
Total Nitrogen (TN) (mg/L)	2 – 35; 5	1 – 170; 7	2 – 4; 3	22 – 45; 23
Total Phosphorus (TP) (mg/L)	10 – 180; 17	1 – 98; 7	0 – 4; 3	4 – 14; 9
Ammonia (mg/L)	0 – 3; 0.2	0 – 35; 1	0 – 1; 0.6	0.1 – 6; 0.2
Volume-Weighted Mean Diameter	30 – 280; 145	13 – 265; 41	140	50 – 450; 120
Specific Surface Area	0.2 – 1.7; 0.5	0.2 – 2.4; 1.1	0.4	0.08 – 0.8; .6
Zeta Potential (mV) (negative values)	31 – 9; 10	14 – 6; 13	2	11 – 6; 11
Conductivity (mS/cm)	0.5 – 1.8; 0.6	0.50 – 1.50; 1.0	0.4	0.8
Sodium Adsorption Rate (SAR)	-	0.16 – 3.67; 1.5	-	2.09
Heavy Metals	BDL - Cu*, Zn*	BDL	-	BDL
E. Coli (cfu/100mL)	BDL – 2.4E+03	2.5E+02 – 3.6E+06; 1.6E+03	BDL	1.3E+02 – 1.6E+03
Coliform (cfu/100mL)	-	1.3E+02 – 4.0E+07; 1.0E+07	BDL	8.0E+05 - 4.3E+06

"BDL" below detection limit. E.Coli and Coliform limit <20 cfu/100 mL

"-" not applicable/insufficient data

*Heavy metals copper (0.28 mg/L) and zinc (0.25 mg/L) were detected in apple wash-waters, may be attributed to water recycling, buildup of contaminants in recycled waters

** Solids greater than 100,000 mg/mL were observed in one particular root crop wash-water

***1,000 is the maximum value on the NTU meter without dilution so therefore it is conservative (Maximum Detection Limit)

Table 3: Performance of On-site Wash-water Treatment Systems.

Facility	A2	C2	G1		G2	MV1	P1	P2	P3	SP1
Treatment Type	IV	I	I	Grasslands	I	II	III	III	II	I
Number of Samples	2	3	3	3	2	3	3	2	2	2
Turbidity	E	P	P	E	P	VG	VG	E	P	P
Transmittance	E	P	S	P	P	P	P	P	P	P
TS	E	P	P	G	S	VG	E	E	P	S
SS	E	P	P	P	G	P	P	P	P	P
TDS	E	P	P	G	E	S	VG	S	VG	S
COD	E	P	P	P	-	P	P	P	P	-
BOD5	E	P	P	E	VG	VG	E	E	VG	P
TOC	E	P	P	P	P	P	P	P	P	-
TN	E	P	P	P	E	P	P	P	P	G
TP	E	P	P	P	-	P	S	P	S	-
Ammonia	E	P	P	G	P	S	E	VG	VG	P
Conductivity	E	P	P	P	-	-	P	VG	P	-
E. Coli (log)	E	P	G	E	P	G	E	P	G	G
Coliform (log)	-	P	P	-	P	P	S	-	-	P

P (<40% removal), S (40-60% removal), G (61-75% removal), VG (76-90% removal), E (>90% removal), "-" not applicable/insufficient data
Treatment Types - I) single settling tank/pond, II) three settling tanks/ponds in series, III) four stage sequential reactors (settling, aeration, nutrient removal, settling), and IV) advanced treatment (MBR + RO + UV).

Table 4: Screening (Sieve) Treatment Results of 10 Different Facilities Washing and Processing Vegetables and Fruits.

Facility	A2	C2	G1	G2	LG1	MV1	P2	P3	SP1	SP2
Operation Type	WP	WP	W	W	W	WP	W	WP	W	W
Tested Samples	1-2	3	2-3	3	1-3	2-3	2-3	1-3	2	1
Turbidity	P	P	P	-	P	P	G	G	P	P
Transmittance	P	S	S	P	P	P	S	P	P	G
TS	P	-	P	VG	-	P	P	-	S	VG
SS	P	P	P	S	S	P	P	P	P	VG
DS	P	-	S	-	-	P	E	-	VG	S

P (<40% removal), S (40-60% removal), G (61-75% removal), VG (76-90% removal), E (>90% removal), "-" not applicable/insufficient data

Table 5: Hydrocyclone Treatment Results of 12 Different Facilities Washing and Processing Vegetables and Fruits.

Facility	A2F1	A2	C2	G1	G2	LG1	MV1	P1	P2	P3	SP1	SP2
Operation Type	W	WP	WP	W	W	WP	W	W	W	WP	W	W
Tested Samples	1	1-2	3	2-3	2	2-3	2-3	3	1-3	1-3	2-3	2
Turbidity	P	P	P	P	-	P	S	P	G	G	P	P
Transmittance	P	P	P	P	-	P	G	P	P	P	P	G
TS	-	P	-	P	E	P	S	-	P	S	P	E
SS	-	S	-	P	VG	P	VG	-	P	P	P	E
DS	-	P	-	P	E	P	P	-	-	P	P	VG

P (<40% removal), S (40-60% removal), G (61-75% removal), VG (76-90% removal), E (>90% removal), "-" not applicable/insufficient data

Table 6: Centrifuge Treatment Results of 14 different wash-waters.

Facility	A1(F1, F2, F3)*	A2	C2	G1	G2	LG1	MV1	P1	P2	P3	SP1	SP2	C1	MV2
Operation Type	W	WP	WP	W	W	W	WP	W	W	WP	W	W	WP	WP
Tested Samples	1	1-2	1-3	1-2	2	1-3	1-3	1-3	1-3	1-3	1-3	1	16	12
Turbidity	VG, P, S	P	VG	E	G	VG	E	E	VG	G	E	E	E	G
Transmittance	P	P	G	S	S	P	VG	E	E	S	VG	E	VG	-
TS	P	P	P	G	E	S	S	G	G	S	S	E	-	-
SS	G, E, VG	S	G	E	E	VG	E	E	VG	E	G	E	E	-
DS	P	VG	P	P	E	P	P	P	P	P	S	VG	-	-
COD	VG, P, P	P	G	E	E	P	G	VG	G	S	P	G	-	-
BOD5	G, P, VG	P	S	VG	S	P	S	S	P	P	P	-	P	P
TOC	VG, P, S	P	S	-	-	-	S	P	P	P	-	-	-	-
TN	P	P	S	G	VG	P	P	P	P	P	G	E	S	-
TP	P	P	P	VG	VG	P	VG	VG	S	G	G	E	P	-
Ammonia	P	P	G	G	VG	P	P	P	P	P	VG	VG	P	-
Conductivity	P	P	P	-	-	P	P	P	P	P	-	-	-	-
E. Coli	BDL	E	-	E	E	BDL	E	-	P	VG	VG	P	E	-

P (<40% removal), S (40-60% removal), G (61-75% removal), VG (76-90% removal), E (>90% removal), "-" not applicable/insufficient data
*F1 – Flume 1, F2 – Flume 2, and F3 – Flume 3

Table 7: Settling Without any Chemical Aid, Natural Settling Results of 14 different Wash-waters

Facility	A1 (F1, F2, & F3)*	A2	C2	G1	G2	LG1	MV1	P1	P2	P3	SP1	SP2	C1
Operation Type	W	WP	WP	W	W	W	WP	W	W	WP	W	W	WP
Tested Samples	1	1-2	1-3	1-2	1-2	1-3	1-3	1-3	1-3	1-3	1-3	1	1
Turbidity	G, S, P	P	VG	G	P	G	G	P	P	P	S	G	P
Transmittance	P	P	G	S	P	P	G	VG	P	P	P	E	P

P (<40% removal), S (40-60% removal), G (61-75% removal), VG (76-90% removal), E (>90% removal), "-" not applicable/insufficient data
*F1 – Flume 1, F2 – Flume 2, and F3 – Flume 3

Table 8: Settling with C&F Treatment Results of 13 different Facilities.

Facility	A1 (F1,F2,&F3)*	A2	C2	G1	G2	LG1	MV1	P1	P2	P3	SP1	SP2	C1
Process Type	W	WP	WP	W	W	W	WP	W	W	WP	W	W	WP
Tested Samples	1,1,1	1-2	1-3	1-2	2	1-3	1-3	1-3	1-3	1-3	1-3	1	5
Turbidity	VG	E	E	E	E	E	E	E	E	E	E	E	VG
Transmittance	P	E	E	G	E	S	E	E	E	E	VG	E	-
TS	-	-	S	S	E	G	P	VG	VG	G	S	E	-
SS	-	-	E	E	E	E	E	E	E	E	VG	E	-
TDS	-	-	P	P	VG	G	P	S	P	P	S	VG	-
COD	-	P	E	VG	VG	P	VG	E	VG	S	E	G	-
BOD5	-	-	-	-	P	P	G	-	VG	P	-	P	-
TOC	-	P	G	-	-	P	VG	G	VG	P	-	-	-
TN	-	P	G	VG	VG	P	P	S	S	P	VG	E	-
TP	-	E	VG	E	E	P	E	E	VG	E	E	-	-
Ammonia	-	VG	-	VG	G	S	VG	P	P	P	VG	G	-
Conductivity	P	-	P	P	-	-	P	P	P	-	P	-	-
E. Coli	BDL	-	E	VG	E	BDL	E	-	E	E	VG	G	-
Coagulants	-	N, C	N	N, P	C	N	N, P	N	N, C	C	N	N	F, A
Dosage (mg/L)	-	200, 50	25-100	200, 25	150	10	25-50, 200	50-200	150-250, 25	25-150	5-200	25	2000

P (<40% removal), S (40-60% removal), G (61-75% removal), VG (76-90% removal), E (>90% removal), "-" not applicable/insufficient data
*F1 – Flume 1, F2 – Flume 2, and F3 – Flume 3

N - Nalco ULTRION 8187 (Aluminum Chloride Hydroxide),
C - Chitosan (a polysaccharide),
S - Sigma-Aldrich (Poly(diallyldimethylammonium chloride)),
P - Polyglu (Water Treatment Agent PGα21Ca),
A - Aluminum Sulphate - $Al_2(SO_4)_3 \cdot 14H_2O$,
F - Ferric Chloride - $FeCl_3 \cdot 6H_2O$.

Table 9: DAF Treatment Results of 13 different Facilities.

Facility	A2	C2	G1	G2	LG1	MV1	P1	P2	P3	SP1	SP2	C1	MV2
Process Type	WP	WP	W	W	W	WP	W	W	WP	W	W	WP	WP
Tested Samples	1	1-3	1-2	2	2-3	1-3	1-3	1-3	1-3	1-3	1	16	4
Turbidity	P	P	VG	VG	E	VG	-	E	VG	S	E	E	E
Transmittance	VG	VG	S	E	S	VG	-	E	VG	G	E	E	E
TS	-	S	S	E	P	S	VG	VG	G	S	E	-	-
SS	VG	VG	E	E	-	VG	E	E	E	VG	E	E	E
TDS	-	P	P	E	P	P	S	S	P	P	VG	-	-
COD	P	E	VG	E	P	G	E	E	S	VG	G	-	-
BOD5	-	-	E	P	P	P	-	-	P	E	-	S	S
TOC	P	S	-	-	S	G	G	VG	P	-	-	-	-
TN	P	G	G	E	P	P	G	G	P	G	E	G	-
TP	E	S	E	E	S	E	-	G	E	VG	G	G	-
Ammonia	P	P	VG	VG	S	VG	P	P	P	S	G	P	-
Conductivity	-	-	-	-	-	P	-	-	-	-	-	-	-
E. Coli	E	-	VG	E	BDL	E	-	E	E	VG	E	E	-

P (<40% removal), S (40-60% removal), G (61-75% removal), VG (76-90% removal), E (>90% removal), "-" not applicable/insufficient data

Table 10: EC Treatment Results of 11 different Facilities.

Facility	A2	C1	G1	G2	*LG1	*MV1	P1	P2	*P3	SP1	*SP2
Process Type	WP	WP	W	W	W	WP	W	W	WP	W	W
Tested Samples	1-2	3	2	2	2	1-3	1-3	1-3	1-3	1-3	1
Turbidity	VG	G	E	E	-	E	-	S	E	E	E
Transmittance	E	-	VG	E	-	E	-	E	E	VG	-
TS	S	-	G	E	P	S	S	G	G	S	E
SS	P	-	E	E	P	E	E	G	E	P	E
TDS	S	-	S	E	P	P	P	S	S	G	VG
COD	G	G	E	E	P	G	P	E	VG	E	E
BOD5	P	-	-	-	-	S	-	P	S	-	-
TOC	P	-	-	-	P	P	P	-	S	-	-
TN	P	G	VG	E	P	S	P	E	G	P	E
TP	VG	-	E	E	S	E	VG	VG	E	VG	E
Ammonia	P	-	G	G	P	P	P	P	P	G	E
Conductivity	P	P	-	-	P	P	-	-	-	-	-
E. Coli	P	-	E	E	BDL	E	-	E	E	E	E

P (<40% removal), S (40-60% removal), G (61-75% removal), VG (76-90% removal), E (>90% removal), "-" not applicable/insufficient data
*Samples were tested with second electrocoagulation setup, see Materials and Methods section for more details.

Table 11: Decision Matrix for Bench-scale Treatment Performance for Reducing Solids as Measured by Turbidity, Transmittance, and SS of various wash-water and operation types.

SOLIDS	Settling		C&F		DAF		Centrifuge		HC		Screening		EC	
Operation Type	W	WP	W	WP	W	WP	W	WP	W	WP	W	WP	W	WP
Potato	P	P	E	E	E	VG	E	G	P	G	G	G	G	E
Sweet Potato	S	-	E	-	VG	-	E	-	P	-	P	-	E	-
Ginseng	G	-	E	-	E	-	E	-	P	-	P	-	E	-
SP2 and G2 (no soil control)	G,P	-	E	-	E	-	E	-	E	-	P	-	E	-
Carrot	-	G-P	-	E	-	VG	-	VG	-	P	-	P	-	G
Mixed Veg	-	G	-	E	-	VG	-	E	-	VG	-	P	-	E
Leafy Greens	G	-	E	-	VG	-	VG	-	P	-	P	-	P	-
Apple	G-P	P	VG	E	-	VG	G	S	P	P	-	P	-	P
P (<40% removal), S (40-60% removal), G (61-75% removal), VG (76-90% removal), E (>90% removal), "-" not applicable/insufficient data														

Table 12: Decision Matrix for Bench-scale Treatment Performance for Reducing COD of Various Wash-water and Operation Types.

COD	C&F with Settling		DAF		Centrifuge		EC	
Operation Type	W	WP	W	WP	W	WP	W	WP
Potato	E	S	E	S	VG	S	E	VG
Sweet Potato	E	-	VG	-	P	-	E	-
Ginseng	VG	-	VG	-	E	-	E	-
SP2 and G2 (no soil control)	G,VG		G,E		G,E		E	
Carrot	-	E	-	E	-	G	-	G
Mixed Veg	-	VG	-	G	-	G	-	G
Leafy Greens	P	-	P	-	P	-	P	-
Apple	-	P	-	P	P	S	-	G
P (<40% removal), S (40-60% removal), G (61-75% removal), VG (76-90% removal), E (>90% removal), "-" not applicable/insufficient data								

Table 13: Decision Matrix for Bench-scale Treatment Performance for Reducing TN & TN of Various Wash-water and Operation Types.

TN & TP	C&F with Settling		DAF		Centrifuge		EC	
Operation Type	W	WP	W	WP	W	WP	W	WP
Potato (TN;TP)	S;E	P;E	G;G		P;VG	P;G	E;VG	G;E
Sweet Potato	VG;E	-	G;VG	-	G;G	-	P;VG	-
Ginseng	VG;E	-	G;E	-	G;VG	-	VG;E	-
SP2 and G2 (no soil control)	E;-, VG;E	-	E;G, E;E	-	E;E, VG;VG	-	E;E, E;E	-
Carrot	-	G;VG	-	G;S	-	S;P	-	S;-
Mixed Veg	-	P;E	-	P;E	-	P;VG	-	S;E
Leafy Greens	P;P	-	P;S	-	P;P	-	P;S	-
Apple	-	P;E	-	P;E	P;P	P;P	-	P;VG
P (<40% removal), S (40-60% removal), G (61-75% removal), VG (76-90% removal), E (>90% removal), "-" not applicable/insufficient data								

Table 14: Decision Matrix for Bench-scale Treatment Performance for Reducing E.Coli of Various Wash-water and Operation Types.

E.Coli	C & F with Settling		DAF		Centrifuge		EC	
Operation Type	**W**	**WP**	**W**	**WP**	**W**	**WP**	**W**	**WP**
Potato (TN;TP)	E	E	E	E	P	VG	E	E
Sweet Potato	VG	-	VG	-	VG	-	E	-
Ginseng	VG	-	VG	-	E	-	E	-
SP2 and G2 (no soil control)	G,E	-	E;E	-	P;E	-	E	-
Carrot	-	E	-	-	-	-	-	-
Mixed Veg	-	E	-	E	-	E	-	E
Leafy Greens	BDL	-	*	-	BDL	-	*	-
Apple	*	-	*	E	*	E	*	E

P (<40% removal), S (40-60% removal), G (61-75% removal), VG (76-90% removal), E (>90% removal), "-" not applicable/insufficient data
* - Below Detection Level for Raw Sample (Characterization)
BDL – Below Detection Level