The Development of Models to Predict the Characterization and Treatment Feasibility for Fruit and Vegetable Wash-water

by

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ABSTRACT

THE DEVELOPMENT OF MODELS TO PREDICT THE CHARACTERIZATION AND TREATMENT FEASIBILITY FOR FRUIT AND VEGETABLE WASH-WATER

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Large quantities of fresh water are used for washing and processing fruits and vegetables. Post-harvest processing includes washing of soils from root vegetables to washing tree fruit for sanitization, in addition to the cutting and peeling of fresh-cut fruits and vegetables. Variabilities from one facility to another also exist due to differences in washing and processing units for the different fruits and vegetables. As such, the generated wastewater or wash-waters vary significantly in terms of water quality, making it challenging to treat. Compounding the problem is the lack of tools for determining wash-water/wastewater quality parameters and treatment feasibility for disposal or reuse applications.

The research herein hypothesized and proved that wash-water treatment decision tools (models derived using power-rank, multiple linear regression (MLR) and artificial neural network techniques (ANN)) can be developed for wash-waters for the fruit and vegetable industry. This overall goal is achieved by first characterizing wash-waters followed by bench-scale treatment to target solids, effective reduction of solids is key. Level of water quality parameters varied significantly, for example, SS ranged from 43 – 140 mg/L for tree fruit, 182 – 12,730 mg/L for root crops, 30 – 215 mg/L for leafy greens, and 290 – 650 mg/L for mixed wash-waters. On-site membrane bioreactor (MBR) achieved greater than 90 % reduction in all water quality parameters, while biological and settling treatments varied from 40 – 90 % reduction, depending on water quality parameter.

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 efficiency of the tested treatments. The Power-Rank models were created to easily determine raw wash-water quality parameters. The final objective consisted of taking all treatment data and further processing it to develop treatment effluent water quality prediction tools by using multiple linear regression (MLR) and artificial neural network (ANN) analysis. A cost-benefit analysis was also incorporated to determine treatment and operational costs in terms of dollar per cubic meter of water treated ($\$/m^3$). These findings and tools are useful to growers/producers in determining treatment options that did not previously exist.

Acknowledgments

First, I would like to extend a sincere thank-you to my advisor, Dr. Richard G. Zytner for his remarkable guidance and patience throughout the doctoral study. Similarly, I would like to thank Dr. Keith Warriner and Dr. Bahram Gharabaghi for their support on the project, review of my work, and suggestions for improvement. I would also like to thank Tim Brook for his support and feedback on the project. I like to thank the entire graduate staff within the School of Engineering for helping me address technical and administrative hurdles.

I would like to thank the Ontario Ministry of Agriculture and Food and Ontario Ministry of Rural Affairs for providing the financial funding to carry out research and work for compiling this report. In addition, I would like to thank all stakeholders who were great in providing and helping me gather information/data for the project, particularly Rebecca Short, Deanna Nemeth, Tim Brook, and the numerous organizations and individuals within Fruit and Vegetable Growers Association, for their cooperation and in-kind support. Big thanks to our industrial partners, producers, farmers, and processors for providing their facilities for sampling of wastewaters and wash-waters.

A special thank-you is also to all my friends and fellow graduate students who have provided me with the most memorable experience of my graduate student life, both on campus and off-campus. I would also like to take this opportunity to thank my family and friends for their support. A very special thank-you to my beloved wife for her endless support, patience, and sacrifices during this project.

"I have no special talents. I am only passionately curious." -Albert Einstein

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List of Abbreviations

$x_{i,k}$	Independent variable
x_i	Input value
x_{max}	Maximum value in the input series
y_i	Dependent variable
z_i	Normalized value
β_0	Constant or intercept
β_k	Coefficient regression vector or slope
ε_i	Random measured error
µ	Location
m	Mean
ν	Variance
σ	Scale
$Al(OH)_3$	Aluminum hydroxide
ANN	Artificial neural network
BES	Bioelectrochemical systems
BIO4	Sequential batch reactor – four stages
BMP	Best management practices
BOD	Biochemical oxygen demand
C	Centrifuge
C&F	Coagulation and flocculation
CD	Chlorine dioxide
C_f	Final concentration
C_i	Initial concentration
CI	Confidence interval (Chapter 4)
ClO_2	Chlorine dioxide
COD	Chemical oxygen demand
CV	Coefficient of variation
DAF	Dissolved air flotation
DBP	Disinfection by-product
E	Excellent reduction efficiency (>90% removal) (Chapter 3)
E. coli	Escherichia coli
EC	Electrocoagulation
EC	Electrical conductivity (Chapter 4)
EPA	Environmental Protection Agency
FCFV	Fresh-cut fruit and vegetable
FWSF	Free water surface flow
G	Good reduction efficiency (61-75% removal) (Chapter 3)
HC	Hydrocyclone
HPU	High power ultrasound
HSSF	Horizontal subsurface flow
JTCont	Natural settling under the influence of gravity
KS	Kolmogorov-Smirnov goodness-of-fit

List of Abbreviations Continued

MAPE	Mean absolute percent error
MBR	Membrane bioreactor
MBR+RO+UV	Membrane bioreactor with reverse osmosis and UV disinfection
MFC	Microbial fuel cells
MLP	Multilayer perceptron
MLR	Multiple linear regression
MOECC	Ministry of Environment and Climate Change
NaClO	Sodium hypochlorite
NEW	Neutral electrolyzed water
NH_4-N	Ammonia as nitrogen
$\bar{O}$	Average of the observed series
O_i	Observed value
OMAFRA	Ontario Ministry of Agriculture, Food and Rural Affairs
P	Poor reduction efficiency (<40% removal) (Chapter 3)
PAA	Peroxyacetic acid
$\bar{P}$	Average of the predicted series
P_i	Predicted value
PWQO	Provincial Water Quality Objectives
R^2	Coefficient of determination
RMSE	Root mean square error
RO	Reverse osmosis
S	Satisfactory reduction efficiency (40-60% removal) (Chapter 3)
S	Screening (Chapter 5)
SBR	Sequential bioreactor treatment
SET1	Single settling tank treatment
SET2	Two-stage two tanks settling treatment
SET3	Three stage three tanks settling
TDS	Total dissolved solids
TKN	Total Kjeldahl Nitrogen
TN	Total nitrogen
TP	Total phosphorus
TS	Total solids
TSS	Total suspended solids
USEPA	United States Environmental Protection Agency
UV	Ultraviolet
VG	Very Good reduction efficiency (76-90% removal) (Chapter 3)
W	Washing wash-waters
WP	Washing including processing wash-water

Author's Declaration

This thesis consists of material all of which I authored or co-authored: see Statement of Contributions included in the thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Statement of Contributions

Chapter 3, 4, and 5 of this thesis consist of papers that were co-authored by myself, my advisor, Dr. Richard Zytner, and my co-advisors Dr. Keith Warriner and Dr. Bahram Gharabaghi. I developed the overall methodology and experimental design. I carried out the majority of the data collection and lab experiments with the help of co-op students. I analyzed the experimental data to formulate and develop the treatment decision matrices, power-rank models, and treatment prediction models. I documented the results into journal papers and the co-authors assisted with editing and providing feedback. Dr. Zytner, Dr. Warriner, and Dr. Gharabaghi provided their expertise and guidance in water and wastewater treatment, food processing waters and microbiology, and model developments using regression and artificial neural networks methods, respectively.

Chapter 1: Introduction

1.1 Overview

Freshwater, once an abundant source is now becoming scarce, which has a significant impact on the environment and humans. Many parts of the world have polluted rivers, lakes, and groundwater because of heavy industrialization, overpopulation, urbanization, agricultural activity, and simple disregard for nature and regulatory compliance. Water scarcity is further exacerbated by the changing climate, leading to deteriorated water quality, water shortages, dry periods, severe rainfall, and forest fire events putting water sources at risk. Protection of source waters is very important as many lakes have sensitive aquatic life and ecosystems, with a direct impact on human food and health, as well as recreational use of waters. Source water protection has become an integral part of any modern economy including those in the developing countries, as water is essential for humans to survive. To protect ecosystems and human health, stringent environmental laws and regulation on water taking, effluent release and waste management have been enacted. These regulations have a significant impact on many water-intensive industries, such as the agriculture industry.

Canada, with its many lakes, including the Great Lakes, has an abundant source of fresh water. However, many of its lakes are under stress from receiving the excessive level of nutrients from wastewaters from different sectors including agricultural activity, leading to algae blooms (Carmichael and Boyer, 2016; Michalak et al., 2013). Current trends show agriculture is predicted to expand significantly due to growth in world population. This translates to higher demand for vegetables and fruits, requiring large quantities of water for production and post-harvesting activities such as washing and processing to make the product ready for market sale. Fruit and vegetable washing and processing require the use of large quantities of water. Water is an absolute necessity and a key part of the agri-food industry, which include the fresh-cut fruits and vegetables (FCFV) industry or minimally processed fruits and vegetables, including producers and farmers requiring washing of products to get ready for markets/grocery stores. Agri-food is defined as relating to the commercial production of food by farming.

Industries involved in fruit and vegetable washing and processing use large volumes of fresh water to wash the soils of root vegetables after harvest (Kern et al., 2006). In addition, water is also used for cutting, peeling, polishing, sanitization (Lehto et al., 2014). In some cases, water is used to transport the products from one stage of the process to another and to quickly cool the product. The large volumes of fresh water used can produce an equivalent amount of wastewater requiring adequate treatment and disposal (Lehto et al., 2009; Olmez and Kretzschmar, 2009). The term wash-water and wastewater may be used interchangeably in this industry. However, a key difference is that wash-water refer to waters used to wash the fruits and vegetables that may be recirculated in dump/dunk tanks to perform multiple wash cycles. The wash-waters are disposed of at the end of the cycle, either after a single use (for more intensive processes like peeling and cutting), or end of the day/week (for less intense processes like washing, rinsing, and/or microbial control). This is dependent on the product and process type being washed/processed. At this point, it becomes wastewater as it requires disposal and is subjected to by-laws and regulatory limits for compliance.

Due to the substantial volumes of waters involved in the washing and processing industry, it is important to practice water conservation through minimizing water use and water reuse;

effectively reducing the water needed to wash and process fruits and vegetables. Increased demand for fresh-cut fruit and vegetable products has resulted from trends toward healthier foods, which are offered by incorporating fruits and vegetables with meals, such as salad (Bhupathiraju et al., 2011). Combined with the trend towards more people eating out and the oversize serving provided at some restaurants. Long-term trends show increasing demand for fruits and vegetable, as a result, increased use of fresh water for process needs leading to equivalent amount of wash-waters requiring treatment.

The wash-waters can contain heavy loads of solid matter in the form of dissolved and particulate matter, nutrients (nitrogen & phosphorus), and pathogens. These constituents can be a nuisance to the natural environment when released into rivers and lakes, disrupting the health of the lakes which ultimately affects the fish we eat and use of lakes for recreational activity. The increased volumes of effluent (treated or untreated) released over the last decade have raised concern, causing fruit and vegetable washing and processing industries to be more diligent in implementing better practices for wash-water treatment and reuse to reduce overall water consumption. For these reasons and due to the limited research, that exists in the literature on characterization, treatment feasibility, and especially treatment prediction tools for fruit and vegetable washing and processing industry, the need for cost-effective solutions is evident.

The research herein explores the characterization of physio-chemical water quality parameters of wash-water and wastewaters generated from washing and processing fruits and vegetables requiring treatment for disposal and reuse. This will aid in expanding what we know about the water quality parameters and their variabilities to better define the problem. Additional datasets obtained from OMAFRA were combined to derive ranks/equations for calculating water quality. Treatment efficiencies were studied for existing on-site water treatment systems/trains to understand the reduction in the level of solids and other water contaminants. The bulk of the research was focused on conducting bench-scale testing of solid removal technologies, using the collected wash-water and wastewater sampled from different operations involved in washing and processing (cutting/budding/peeling) of fruits and vegetables. The collected data from bench-scale testing of water treatment technologies was utilized to develop treatment decision matrices. These can provide an indication of treatment performance based on the type of product (Carrot, Potato, Apple, etc.) and the type of process employed (washing or processing or both). The data was further processed to develop predictive models for estimating the level of treated effluent water quality such as the level of suspended solids in the treated waters, which can be used to assess reuse of water, based on water quality, or for assessing disposal/release into the natural environment. See Appendix E for more information on data, sources and availability. In combination, all the findings including the differently developed power-rank, multiple linear regression, and artificial neural network models, can provide sufficient details for assessing wash-water treatment, and serve as valuable works. Adding to the limited existing research and addressing gaps in the literature.

1.2 Research Motivation

1.2.1 Background

The fruit and vegetable washing and processing industry include, the fresh-cut and minimally processed fruit and vegetable industry, and producers and farmers washing and processing fruits and vegetables to get ready for market or grocery stores. Altogether the processors make a variety of food products, which can range from washed bagged potatoes to ready-to-eat peeled baby carrots. Minimally processed foods are raw fruits and vegetables that have been sliced, chopped, peeled, and/or shredded before they are packaged for grocery stores and food markets. The intensity (washing in comparison to cutting/peeling) of processing depends on the type of fruit or vegetable and the many stages of processing required to get the product ready for market.

Studied facilities show that there are usually three main stages of processing (1) soil washing (2) cutting/peeling/processing (3) disinfection/packaging. Water may also be used in flumes to transport and sanitize product, for example, the use of water flumes in apple washing and sanitization. In addition, water is used for in place cleaning of the equipment and facilities used for washing and processing fruits and vegetables. Soil washing of the product is mostly done at farms after harvesting the product. The amount of soil attached to the product is dependent on the soil type and type of vegetable/fruit, which mostly affect root vegetable, above ground, and leafy green and not so much for tree fruits. Leafy greens and above ground vegetables have insignificant soil compared to root vegetables. Wash-water from soil washing stage contain heavy loads of soils with varying ratios of sand, silt and clay. The second and third stages are where the product is cut, peeled/sliced, rinsed, disinfected, and packaged producing wash-water rich in organic matter, pathogens, and residual disinfectant and sanitizing agents. Essentially, the characteristics of the wash water are dependent on soils, produce constituents and degree of dilution.

These different stages of processing impact the characteristics of wash-water, which is often interchanged with the term wastewater. Wash-water refers to water used in fruit and vegetable washing and processing operations to wash, process, and sanitize the product, often several batches of the products are washed with the same water without any treatment (Salomonsson et al., 2014). After the wash cycle, the wash-waters are disposed of as wastewater. However, some stages of the process may only use the water once before requiring discharge as wastewater, such as cutting/peeling stages of the process. Thus, wash-water and wastewater are often interchanged. It is important to note that the wash-waters from fruit and vegetable washing and processing industry do not contain a mixture of contaminants commonly found in domestic and agricultural wastewater, such as feces from humans and farm animals. In some cases, wash-water from fruit and vegetable washing and processing may be mixed with other farm/agricultural wastewater (cattle or hog). To stay consistent with terminology used by Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA), provincial regulatory body, the term "wash-water" will be used from here on when referring to any wastewater generated from fruit and vegetable washing and processing (Nemeth, D., Shortt, R., and Brook, T., personal communication, 2013).

Wash-waters are rich in soils, organic matter, and pathogens, as such must be treated to achieve regulatory standards before releasing into the environment. Untreated wash-water released into water bodies can lead to many problems for aquatic and eco-system systems, wildlife, and humans (Singh et al., 2004). One example which effects everything is eutrophication, whereby algae grows in waters because of excessive levels of nitrogen and phosphorus within the water body (Schindler et al., 2016). Wash-waters high in BOD and COD (organic loading) can deplete oxygen from water bodies, which impact the fish and aquatic life.

To reduce solids many producers and processors have utilized various treatment methods to manage their wash-water. Methods such as settling tanks and ponds are commonly used at both farm scale and large-scale facilities (Kern et al., 2006). The goal of the settling process is to reduce solids such as grit, silt, sand, particulate matter and other settable materials from wash-waters. However, this does not deal with dissolved solids (a function of BOD) and chemical constituents (TP and TN). In many cases current wash-water treatment processes are not adequate to allow one to meet regulatory standards. Wash-water is considered to have the same magnitude of impact on the environment as industrial wastewater and is therefore regulated by the Ministry of Environment and Climate Change (MOECC). However, this statement may not be entirely true as there is very large variability in wash-waters. OMAFRA has also received many requests for investigation of wash-water treatment and management (Nemeth, D., Shortt, R., and Brook, T., personal communication, 2013). MOECC and OMFRA have identified a need for research into effective wash-water treatment methods for Ontario's FCFV producers and processors, in addition to developing tools (decision matrix and regression/neural network models) to assist in evaluating potential treatment technologies.

1.2.2 Research Gap and Objectives

The main goal of this research was to gain a better understanding of the challenges that persist surrounding the treatment of wash-waters from different fruit and vegetable washing and processing facilities. The need for an exhaustive understanding of wash-waters characterization and treatment is necessary due to the lack of research resulting from the large variety of fruits and vegetable washed and processed. The industry deals with many different categories of fruits and vegetables ranging from tree fruits, root vegetables, leafy greens, to above ground, making it challenging to characterize all wash-waters individually or providing treatment options specific for each type of wash-water. Assessment of all wash-water at once under a holistic approach is also lacking, which can allow a better understanding of the risks posed by certain wash-water compared to other in terms of the magnitude of their water quality parameters, for example, which wash-waters have the highest BOD and TSS. Generic wastewater treatments are available but small to medium enterprise require more economically feasible treatment technologies where the research is lacking. Water and wastewater treatment, management, and reduction are very important in this industry, due to the large use of water, if reduced can lead to economic savings that reduce costs and secure water for process needs.

The research gap is the lack of information on wash-water and wastewater water quality characteristics to enable treatment technology matching, in addition to the holistic assessment of water quality parameters needed of all types of wash-water and wastewaters from fruit and vegetable washing industry. The investigation into physiochemical treatments, which are effective at removing solids, could be used to mitigate contamination in wash-water for reuse and disposal applications. Current and existing treatments encompass both simple physical (settling ponds and tanks), biological (4 stage) and advanced treatment like a membrane bioreactor (MBR) to produce different quality water for reuse and disposal. However, information on the performance of wash-water treatments has not been compared amongst many different treatments technologies at once or in parallel at an extensive scale, such as the one outlined in this study. In addition, water quality characteristics are also lacking for different wash-waters that exist in Ontario. This study is also useful for other geographical areas given the underlying assumptions match up, such as soil types, product types, and processing methods.

Due to the future growth of the industry, the importance of securing water resource and water management, and to meet disposal/reuse regulations, the need for a water treatment feasibility tools was of greatest interest. This research will add to the existing body of knowledge surrounding wash-water characteristics and corresponding treatment through the development of predictive tools which follow the methodological framework highlighted in this study. It will also provide a simple, practical approach to identify wash-water characteristics and the guidance on the identification, performance, and selection of treatment systems, based on pollutant loadings and facility operational parameters. In principle, this research seeks to improve and further develop characterization of fruit and vegetable washing and processing wash-water and wastewaters, the treatment selection process, by providing design tools to estimate the quality of treated waters to assess against regulatory compliance limits for reuse or disposal. To meet these primary objectives, the following tasks were identified:

1. Assess and characterize wastewaters and wash-waters based on product, process, and water quality parameters from different fruit and vegetable operations in Southern Ontario. Understanding water quality parameters such as total solids, suspended solids, dissolved solids, total nitrogen, total phosphorus, ammonia as nitrogen, electrical conductivity, pathogens can provide insight into contaminants of concern, for the different products and processes as they generate wash-waters.
2. Assess on-site treatments and their effectiveness for reducing different water quality parameters. Evaluate different on-site treatment types contained in the study, ranging from settling tanks to biological treatment to MBRs.
3. Determine and assess bench-scale treatments for reducing solids (Screening, Hydrocyclone, Settling, Settling with Coagulation and Flocculation (C&F), Centrifuge, Dissolved air flotation (DAF), and Electrocoagulation).

4. Develop decision matrices (treatment tables) from bench-scale testing and analysis to provide an estimate of treatment efficiency, based on wash-water (product), process, and treatment type.
5. Analyze additional datasets from OMAFRA and perform a combined analysis of all data, including data collected during Ph.D. work. Provide a power-rank tool for assessing risk from the magnitude of different wash-waters quality parameters against effluent limits designed to protect ecosystems within the streams, rivers, and lakes. Which would rank the different water quality parameters from worst to best in terms of total suspended solids (TSS), total dissolved solids (TDS), total solids (TS), chemical oxygen demand (COD), biochemical oxygen demand (BOD), total nitrogen (TN), total phosphorus (TP), nitrogen as ammonia (NH_4-N), and electrical conductivity to determine risk to ecosystems. As well as allow for estimation of different water quality parameters as mentioned previously.
6. Develop models to predict and evaluate the feasibility of different wash-water treatment technologies. By extending the decision matrices from Objective 4 and adding data from Objective 5, the information can be converted to mathematical models utilizing multiple linear regression (MLR) and artificial neural network (ANN) techniques.
7. Incorporate a cost-benefit analysis into the prediction tools (MLR and ANN) to highlight the selection of the appropriate treatment process based on operating and capital costs, facility operational parameters, and benefits from water reuse.
8. Incorporate the results from Objective 5 – a power-rank tool for raw wash-water characterization, Objective 6 – MLR and ANN models for prediction of treated water quality, Objective 7 – economic analysis and costings associated with treatment

implementation and comparison to regulatory limits into a single excel worksheet or Wash-water Toolkit. The Wash-water Toolkit will provide stakeholders with simple and effective tools to better understand wash-water characterization, potential treatment options and whether they meet regulatory limits set by municipalities or provincial water quality objectives, and also their corresponding capital and operating costs.

1.3 Organization

This thesis is organized in a manuscript format in accordance with the "Thesis Format" section of the University of Guelph Graduate Calendar. The chapters highlight the separate elements of the research project. As such, Chapters 3 through 5 are separate papers, while the other chapters serve to introduce, support, and provide conclusions/recommendations to the study, and are summarized as follows:

1.3.1 Chapter 1 – Introduction

This chapter serves as an introduction to the body of work contained within this thesis as part of the doctoral research program. It provides key information, which is outlined in the overview, background, research gap and objectives. It also provides brief outlines of the subsequent chapters, some of which have been published/under review/in preparation as separate papers.

1.3.2 Chapter 2 – Literature Review

This chapter provides an in-depth literature review of existing wash-water characterization, treatment methods available for solids reduction, and applicable regulations surrounding reuse and disposal. The chapter lists the different solids reduction technologies studied, additional wastewater treatment, and disinfection. Summary of relevant work is highlighted at the end of the chapter.

1.3.3 Chapter 3 – Fruit and vegetable wash-water characterization, treatment feasibility study and decision matrices

This chapter provides an overview of the different water quality characteristics expected from different wash-waters. Current on-site treatments were assessed for removal efficiencies of solids and other secondary wastewater contaminants, such as BOD, TN, TP, pathogens that are reduced due to a reduction in solids. Six physiochemical treatment technologies were assessed through bench-scale studies and allowed for the construction of decision matrices, which provide an estimate of treatment effectiveness. Wash-water and operation parameters were identified and correlated with treatment type and effectiveness. This can be useful in understanding the behaviour of various wash-water with treatment technologies and is a starting point for treatment implementation analysis. The work fulfils objectives one, two, three and four, as highlighted in the Research Gap and Objectives section. The work was submitted and published in the peer-reviewed journal *Canadian Journal of Civil Engineering* and is cited as follows:

- *Mundi, G. S., Zytner, R. G., & Warriner, K. (2017). Fruit and vegetable wash-water characterization, treatment feasibility study and decision matrices. Canadian Journal of Civil Engineering, 11(44), 971–983.*

1.3.4 Chapter 4 – Predicting Fruit and Vegetable Processing Wash-water Quality

This chapter outlines work done on increasing the characterization study and to fill any gaps in data, which were necessary to achieve objective six – modelling. The characterization data was further developed using data provided by OMAFRA. The completed master data set was used to develop power rank models, which can be utilized to understand raw wash-water quality depending on process and product. The Power rank models are simple to use and can be used by anyone to understand the different raw water quality parameters. Such as TSS, TDS, TS, BOD, COD, TN, TP, NH_4-N, and electrical conductivity. The work fulfils objective five as highlighted in the Research Gap and Objectives section. The work was submitted and published in the peer-reviewed, *Water Science and Technology* and is cited as follows:

- *Mundi, G. S., Zytner, R. G., Warriner, K., & Gharabaghi, B. (2018). Predicting Fruit and Vegetable Processing Wash-water Quality. Water Science and Technology. Available online 8 March 2018, wst2018109, DOI: 10.2166/wst.2018.109*

1.3.5 Chapter 5 – Predicting Water Quality

This chapter outlines the work done on modelling the results gathered in objectives one through five. The work presented in the first publication highlights the treatment decision matrices, which are essentially tables to determine treatment reduction efficiency under different conditions. These tables are now converted to numerical equations and functions with the use of multiple linear regression and artificial neural network modelling methods. These can be used to predict the level of treatment achievable under one of the tested treatments in this study. The work fulfils objective six as highlighted in the Research Gap and Objectives section. The work has been prepared and will be submitted to a peer-reviewed journal such as *Water Science and Technology*:

- *Mundi, G. S., Zytner, R. G., Warriner, K., & Gharabaghi, B. (In preparation). Multiple Linear Regression and Artificial Neural Network Models for Predicting Water Quality of*

Treated Fruit and Vegetable Wastewater. Submission planned for Water Science and Technology journal.

1.3.6 Chapter 6 – Economic Analysis

This chapter highlights the cost/benefit analysis which is a core part of any engineering analysis. It is used when considering/estimating costs and project feasibility of wash-water or wastewater treatment system for water recycling. The capital and operating costs, including savings from water recycling, and costs associated with equipment, chemical, electricity, water/wastewater, operator pay, maintenance, etc. The costs for solids handling can also be significant, especially if it is required to be landfilled. The challenges in determining costs, the cost per meter cubic of treated water, and sample water treatment costings are highlighted. The needs, costs, and savings for urban and rural producers are quite different, making it harder to justify implementation in some scenarios. Thus, the benefits should consider the reduction of risks associated with implementing water/wastewater treatment and reuse systems. Such as reduced environmental impact and securing water source for future growth, which is too precious to risk.

1.3.7 Chapter 7 – Conclusion

The final chapter emphasizes the overall contributions made by this doctoral research project and provides recommendations for future work and direction.

Chapter 2: Literature Review

2.1 Overview

Vegetable and fruit washing and processing have been going on for many decades and corresponding industries will continue to grow as recent trends show increasing demand for fresh, freshly prepared, and fresh-cut foods (Alarcón-Flores et al., 2014; Klaiber et al., 2005; Lehto et al., 2014). This is mainly due to the many health benefits offered by eating fruits and vegetables such as preventing cardiovascular diseases and certain cancers (Bhupathiraju and Tucker, 2011; Soerjomataram et al., 2010). In addition to providing our bodies with important components such as antioxidants and possessing anti-inflammatory capabilities (González-Gallego et al., 2010; Kim et al., 2006). Along with the health benefits, ready-to-eat products also provide convenience over conventional methods of food preparation and serving (Klaiber et al., 2005). Increased demand for processed fruits and vegetables leads to increased use of fresh water.

Water is essential for the agriculture and food processing industry. Agriculture is the largest user of fresh water where the water is not returned to the environment but rather consumed in the process of growing food (Pfister et al., 2011; Plappally and Lienhard, 2012). The food industry has a large water footprint and is known to make use of high-quality waters for processing (Mavrov and Belieres, 2000; US Environmental Protection Agency, 2012), with the processing water converted to wastewater (Lehto et al., 2014; Pfister et al., 2011). A major part of the food washing and processing sector is the minimal processed fresh-cut fruit and vegetable sector in Ontario which has experienced modest growth, see Figure 2-1 (Statistics Canada, 2017). Increased processing is evident in plants, factories and farm operations previously only washing produce are now starting to process (cutting/packaging) or pre-prepared fresh-cut sector.

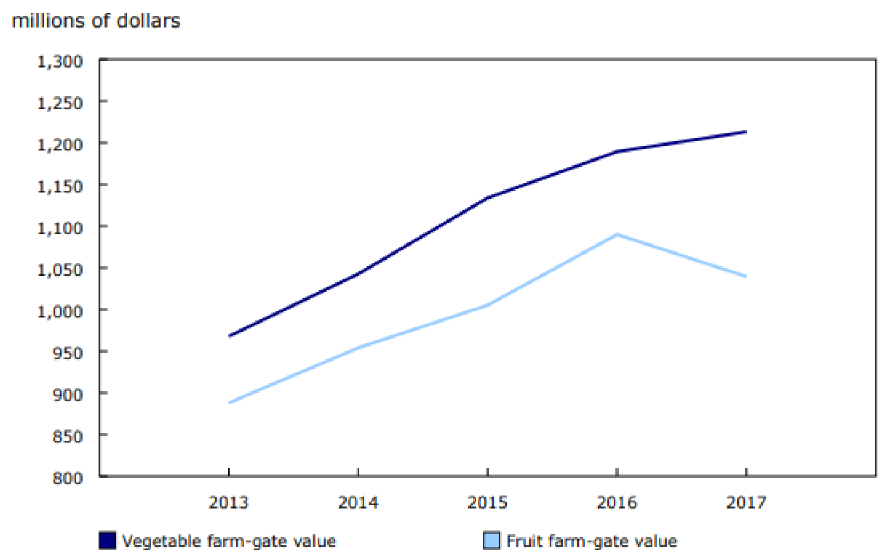

Figure 2-1: Production of fruits and vegetables in Canada from 2013 – 2017

The large volumes of waters used for processing of fruits and vegetables consist of any individual, combination, or all of the following stages: soil washing, cutting, peeling, rinsing, cooling and sanitizing of fruits and vegetables (Casani et al., 2005; Hafez et al., 2007; Kato et al., 2013; Kern et al., 2006; Lehto et al., 2018, 2014, 2011, 2009; Ölmez and Kretzschmar, 2009). Processing of vegetables such as carrots and potatoes make use of drum-style washers and peelers that produce wash-waters rich in organic compounds due to the carbohydrates released from the tap-root (Kern et al., 2006). Organic matter along with a high level of solids make it challenging to treat wash-water, especially from peeling processes, as the dissolved solids do not settle out (Lehto et al., 2009). In place cleaning of processing and conveyance equipment for disinfection and sanitization purposes also require a great deal of water (Lehto et al., 2014). As a result, large volumes of wastewater are generated that require treatment and disposal of solid and liquid waste. Treatment is needed to meet wastewater standards and to eliminate fines imposed if set limits are exceeded. Complicating things is the wide knowledge gap in understanding wash-waters from different stages of fruit and vegetable washing and processing operations and different vegetables.

The composition of the wastewater in the minimal and fresh-cut fruit and vegetable washing and processing industry depends on the stages of processing, as mentioned above. Thus the use of the term wastewater is interchangeable with wash-water. Wash-water refers to water used in fruit and vegetable washing and processing operations to wash, process, and sanitize the product. Often several batches of the same products are washed with the same water without any treatment (Salomonsson et al., 2014).

The heavy use of water within the minimal and fresh-cut fruit and vegetable washing and processing is a major concern and many producers and processors have recognized the need to reduce total water consumption. In addition to realizing the availability of fresh water, there is the surcharge cost for wash-water disposal. Producers and processors serviced by municipal water with sewer access are required to pay for those services, e.g., 1.32 $\$/m^3$ for water taking and 0.99 $\$/m^3$ for wastewater disposal (Region of Peel, 2017). Those facilities having excessive BOD, TSS, TP, Total Kjeldahl Nitrogen (TKN) in their waste stream are levied 0.64, 0.70, 2.24, 1.43 $/kg, respectively (City of Toronto, 2018a, 2018b). Exceedance of a water quality parameters or industrial waste surcharges can be calculated using a surcharge formula defined by the municipality. Water taking and wastewater disposal rates increase 10 % on an annual basis depending on municipality (Region of Peel, 2017; City of Toronto, 2018c).

For these and other reasons, water reuse and management are necessary. Thus, effective treatment and disinfection of wash-water are critical in ensuring successful and safe water recycling in the minimal and fresh-cut fruit and vegetable washing and processing industry. Water reuse in the minimal and fresh-cut fruit and vegetable washing and processing industry has been practiced for some time now, especially in re-circulating with recharging of wash-water for washing and sanitizing of leafy vegetables (European Hygienic Engineering & Design Group, 2007; Salomonsson et al., 2014). Disinfectants such as chlorine are added continuously to maintain the microbiological quality of wash-waters, such as to reduce microbial loading and prevent cross-contamination. Given that there is limited literature on water reuse in the washing and processing of root vegetables and fruits, further investigation on wash-water characteristics, treatments and water reuse is required. The literature review shows some work has been done on understanding the physical, chemical, and microbial qualities of wash-water and wastewater from different fruits and vegetables.

2.2 Characterization

FCFV industry has existed for many decades within Canada and America, and serious research on treatment and disposal of wastewater started to emerge in the 1970s. Two major reports were published which set the baseline for the characterizing and treatment of wash-waters, Fruit and Vegetable Water and Wastewater Management by Chambers and Zall (1979) and Pollution Abatement in the Fruit and Vegetable Industry by USEPA (1977). It is evident from these reports that potato and carrot root vegetables were some of the first to be characterized, and were some of the first reports to present wash-water characteristics from various fruit and vegetable operations that provided comparative analysis. In addition to providing a loading factor that can be used for benchmarking, such as kg of BOD per tonne of product washed ($kgBOD_5$/tonne) it provided an estimate on the cubic meter of water used per tonne of produced washed (m^3/tonne).

Chambers and Zall (1979) point out the importance of pollution prevention practices, water management, and water recycling to combat wastewater management in the fruit and vegetable industry. Detailed analysis of wastewater from beet, pear, cherries and snap beans processing had been outlined by Soderquist et al. (1971), however, blanching-peeling process was used and thus water quality parameters are not easily comparable to minimal and fresh-cut fruit and vegetable washing and processing wash-water. Nevertheless, the study still serves as a good estimate of what to expect as the majority of the processes are the same.

The key drivers behind some of the recent studies are to reduce process water and assess the effectiveness of treating the wash-water and evaluate the potential reuse. Hamilton et al. (2006) from Australia assessed carrot wash-water for reuse potential and reported the high concentration of agrochemicals (chlorpyriphos and linuron) and high levels of turbidity. He suggested the reuse of carrot wash-water for irrigating carrots as means of water recycling but does not recommend it for any other irrigation applications due to a high level of toxicity from linuron. Hamilton et al. (2006) also noted the high risk associated with wash-water reuse due to high levels of E. coli. However, the use of chlorinated water in the final stages of washing carrots substantially reduces this risk. Lehto et al. (2014 & 2009) from Finland looked at carrot and potato wastewater and suggested the separation of soil washing from peeling stages, as 90% of the organic loading is from peeling and processing stages. These findings are in line with Mundi's (2013) report on carrot wash-water analysis and treatment. Kern et al. (2006) in Germany utilized the use of settling basins and wetlands to treat carrot wash-waters, however, dissolved solids were not effectively removed and thus reduced the treatment efficiency of wetlands.

Research conducted by Michigan State University consisting of characterization fruit and vegetable wastewaters but treatment options were not highlighted (Safferman et al., 2007 and 2008). The basic principle of countercurrent flow recycling of water is suggested by Fernandez-torres and Safferman (2008). Countercurrent washing consists of two to three washing stages where fresh water is added to the final washing stage. The water from the final stage is recycled to second wash, and the water from the second stage is recycled to the first stage, while the product moves from first to the final stage. Lehto et al. (2014) has reported that washing and processing (including peeling) of root vegetables use about 1.5–3.0 and 3.5–5.0 m^3 of water per tonne of product, respectively. This serves as a good benchmark when looking at washing processes in Ontario. Research on the characterization of water quality parameters from fruit and vegetable processing exist but are often not comparable to Ontario fresh-cut fruit and vegetable sector due to varying differences in processes (washing or peeling) and geographical factors such as soil types.

2.3 Treatment Methods

There are many challenges in reusing wash-water in the minimal and fresh-cut fruit and vegetable washing and processing industry, one such challenge is determining a treatment train that can provide required chemical and microbial quality water for end use. There are many end-uses consisting of reusing water for soil washing and processing within the facility/plant, irrigation to agricultural land, or augmentation to the natural environment. Thus, the quality of recycling or treated water can vary depending on end use. Characterization of the wash-water is a good starting point in determining the types of treatment processes to be employed, such as physical, chemical, biological or a combination of these. The washing and processing of minimal and fresh-cut fruit and vegetable can result in varying types of wash-water which can differ in concentrations of organic matter and nutrients. Many different treatment technologies are available on the market, thus making the selection process a daunting task. Generic processes are expensive but can use more cost-effective technologies depending on the nature of the wastewater characteristics. Therefore, the selection criteria can include the end use of treated waters, the comparative performance of various technologies, the results of the pilot-scale studies, type of disinfection, future water quality requirements, site constraints, energy and economic considerations (Asano et al., 2007).

2.3.1 Screening (Sieve)

The first step to treating any wash-water is to remove large objects and particles from the wash-water stream that are generated due to washing and processing of minimal and fresh-cut fruit and vegetable. This is done with a screening treatment process. Screening is a water treatment process that use coarse and fine mesh fabrics to retain all particles that are smaller than the mesh openings (Lee, 2007).

Debris and particles also include lost product from the assembly line, an accidental bypass through a cutting or peeling process, or simply doesn't meet the standard of quality set by the operator and thus may end up in the wash-water stream. Screening out large objects such as wasted carrots, potatoes, ginseng roots and other large particles can greatly improve downstream water treatment processes. This is also essential for preventing solids blocking or damaging wastewater feed pumps and sludge pumps. More importantly, coagulant/flocculent consumption is reduced due when removing the particulate matter in wash-waters (Ljunggren, 2006). Both coarse and fine screens are utilized in screening out particles. Coarse screens have openings of 6 mm or greater, fine screens have openings of 1.5 to 6 mm, and very fine screens have openings of 0.2 to 1.5 mm (USEPA, 2003). There are many different types of screening equipment types and configurations on the market that are available for minimal and fresh-cut fruit and vegetable washing and processing operations.

Ljunggren (2006) reported that a filter with an opening of 200 microns is able to reduce SS by 20-35 %, however, this can vary on the type of wastewater. Smaller pore size openings (120 and 60 microns) were also tested but problems with clogging were too frequent from oil and grease. The use of screens in the fruit and vegetable processing industry has been highlighted as early as 1977 as demonstrated by USEPA in Pollution Abatement in the Fruit and Vegetable Industry (1977). Chambers and Zall (1979) highlighted the use of screening (0.06 in or1.6 mm) and four inline centrifugal separators (hydrocyclone) for carrot wash-water treatment and reuse application in California, USA. The effluent from the inline centrifugal separators was treated using two sedimentation ponds which also acted as a reservoir for taking water for fluming carrots. As a result, 15 % of the fresh water into the process was recycled or water demand was effectively reduced by 15 %. It’s a surprise that this study achieved water reuse with only two technologies, however, water quality and food safety were not at all considered. Rotating screens (200 um size openings) have been used in FCFV industry as an effective solids reduction unit process as demonstrated for carrot wash-water and mix vegetable wash-water (Mundi, 2013). Screening is an elementary, simple, and cost-effective initial step in treating wash-waters and thus requires additional investigation on other FCFV. Research is limited for screening and sieve use in the FCFV industry.

2.3.2 Hydrocyclone

Another form of solid-liquid separation equipment is the hydrocyclone. Unlike screening or sieve, the hydrocyclone doesn't have a physical separator. Instead, a vortex is created via the pressure difference (pump) inside the hydrocyclone allowing any heavy solids such as sand/slit to be ejected at the underflow of hydrocyclone. Separation is based on density in addition to the size of the particles. Hydrocyclones have been used in many applications of solid-liquid separation. It has a simplicity of operation, lack of moving parts (other than the pump) and low maintenance costs make it advantageous to use in small-scale 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). The use of hydrocyclone for separating clay from sands for irrigation waters was investigated by Bains and Morgan (1983). Study findings highlight that hydrocyclones have the capacity to separate sand from clay, for clay particles as small as 5 µm. Bains and Morgan (1983) also demonstrated that although theoretical estimation of particle size separation performance exists, there is a limited success in determining the performance in practical settings. Soccol and Botrel (2004) also highlight the capacity of hydrocyclone to remove suspended solids for pre-filtering of irrigation water.

Significant progress has been made to understand the workings of hydrocyclones due to its wide application and use in many industries. With modern computing power and use of computational fluid dynamics software, one can model and understand particle reduction efficiencies, d_{50} for various wastewater streams (Hwang et al., 2012). The shape of the hydrocyclone hasn't changed for decades and the focus of research is in increasing efficiencies, referred to as the cut size, d_{50}. This is defined as the size of the particle that will be removed from the wastewater stream with a 50% efficiency. Any particles larger than the cut size have a greater chance of being removed and any particles less than cut size will be removed with a lower efficiency. Reducing the cut size will allow for the removal of smaller particles more effectively and thus is the focus of many studies in addition to using it for various applications within the wastewater treatment industry (Hwang et al., 2012; Pratarn et al., 2008).

Mansour-Geoffrion et al. (2010) have demonstrated the capacity of hydrocyclones in separating grit from activated sludge. The sludge produced in a biological treatment plants consists of both inorganic (grit) and organic (biodegradable). Grit accumulation reduces biological treatment process efficiencies, thus there is a need to reduce the grit in return activated sludge and mixed liquor (Mansour-Geoffrion et al., 2010). Sludge was first screened through 200, 300 and 500 μm sieves before being pushed through the hydrocyclone to prevent blockage. Low pressure (1.38–5.56 kPa) hydrocyclone have been investigated for solid removal in aquaculture water recycling applications and show promise in removing fish waste materials (Lee, 2015). Limited research is presented in the literature on the use of hydrocyclones for wash-water treatment. This type of technology can be very valuable for wash-water treatment as it often contains both organic (biodegradable) and inorganic (sand/silt) waste materials. Application of this technology to wash-water treatment is limited in literature, therefore, needs further research.

2.3.3 Centrifuge

Another form of mechanical solid-liquid separation process is centrifugation. The main principle is similar to hydrocyclones where rotation forces cause particle separation, based on density and particle size. Various types of centrifuges are available for sedimentation, filtration, and dewatering, as applications for it can be found in all types of industries. Recent development of centrifugation technology are highlighted by Anlauf (2007). Here we will focus on sedimentation/dewatering type centrifuges, where high-speed rotation forces are used to separate solids from liquid in a rotating cylindrical bowl (USEPA, 2000). Centrifuge has been used for many decades to dewater or thicken solids for anaerobic digestion, composting or landfilling. Dewatering also reduces the volume of solids waste, which affects transportation costs for disposal or for by-product use. High solid reduction efficiencies and small footprint design allows for use in multiple applications and is often preferred when dewatering solids.

The use of solid bowl centrifuge in dewatering and reducing solids from a wastewater stream have been comprehensively investigated (Anlauf, 2007; Christensen et al., 2015; Pinkerton and Klima, 2001; Schmidt, 2010). However, the extension to the wash-water application is not evident in literature and thus must be explored.

2.3.4 Coagulation and Flocculation Process (C&F)

The C&F process is widely used in the wastewater industry to precipitate out the particulate and dissolved matter. Three main type of coagulants are used in C&F, metal salts (alum or ferric sulfate) are most common, polyelectrolytes (polymers) are effective but expensive, and natural (chitosan), also very expensive. C&F works on the principle of neutralizing the wash-water particles that are negatively charged. C&F is a two-part process, coagulation, which causes destabilization of repulsive forces which allows for flocculation, agglomeration and formation of particles. Coagulation is achieved by using various chemicals and takes effect on the micro scale. C&F is often combined with settling or floating treatment technologies to enhance solids reduction efficiencies.

The use of chitosan as a coagulant for leafy-vegetable wash-water treatment was assessed by Van Haute et al. (2015b) to increase the reuse potential of post-harvest wash-water. Study findings indicate turbidity reductions of 90% or greater were achieved. However, dissolved solids were not removed and thus disinfection/chlorine demand was not minimized. The study suggests that chitosan is an effective coagulant as a pre-treatment to membrane filtration. The use of coagulation before settling can reduce suspended solids up to 90% which otherwise would be about 35% without coagulation (Sahu and Chaudhari, 2013). Sahu and Chaudhari (2013) conducted an extensive review of chemical treatment for industrial wastewaters which included many industries utilizing coagulation process. Food industry included applications in dairy, meat, and fish processing but limited information was reported for fresh-cut or vegetable processing wastewater. Lehto et al. (2014) and Van Haute et al. (2015c) demonstrated the use of coagulants to increase solid reduction efficiency of settling basins and reduce chlorine demand, respectively. Coagulation can be an expense, however, provides for rapid treatment of wash-water and increased settling rates.

2.3.5 Sedimentation (Settling)

Settling is a primary treatment for many water recycling processes. Settling can provide effective means of reducing solids content in the form of pre-treatment for dissolved air flotation (DAF) or membrane filtration. Many different types of settling tanks and various configuration are available on the market including inclined (plate and tube) settlers. Most applications make use of settling ponds or long rectangular settling tanks, due to cost and treatment effectiveness. Conventional settling treatment methods occupy large footprint. However, this can be overcome by inclined plate settlers (Gregory and Edzwald, 2011). 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 (Gregory and Edzwald, 2011).

Kern et al. (2006) showed that simple settling process can remove coarse and particulate matter effectively for carrot wash-water. Adding aerators improved the reduction of COD and TSS were reduced by 80% (Kern et al., 2006). Utilizing the C&F process along with settling, Hafez et al. (2007) demonstrated the effectiveness as pre-treatment to membrane filtration in wash-water treatment. More recently, sedimentation has been highlighted as an effective pre-treatment technology for carrot wash-water treatment (Lehto et al., 2014). Sedimentation followed by aeration, to stimulate biodegradation, can serve as a very good treatment process to reduce BOD and COD levels. The use of sequential batch reactors (SBR) have also been highlighted in one application for carrot wastewaters treatment and has been shown to be very effective at dealing with batch loads (Lehto et al., 2009). Use of biological treatment may be more suitable for carrot and potato wash-water which include peeling and polishing processes or involved in generating wash-water high in COD and BOD loading. However, cold temperatures reduce efficiency significantly due to reduced biodegradation as a result of reduced microbiological activity (Lehto et al., 2009).

2.3.6 Flotation (DAF)

Flotation is a clarification process with the simple principle of causing the solid particles in wastewater to rise to the top of a flotation tank with the use of fine air bubbles that are produced at the inlet of the flotation tank. Air/water mixture is the main agent of use for flotation, as it produces very fine bubbles as compared to only air. Sedimentation is not good at removing low-density material that may not be easily settable, but DAF can excel for this type of application. 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 was 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.

Surprisingly DAF systems use fewer coagulant doses and produce higher removal efficiencies in comparison to settling with C&F (Khiadani et al., 2014). This study also reported higher sludge production under DAF versus conventional settling processes, which could be attributed to DAF systems' ability to remove solids. Effective operation of DAF systems requires experienced technical staff and accurate control devices. A detailed review of DAF systems and treatment efficiencies are discussed by Edzwald (2010) compiled in an intensive literature review on DAF systems. Wang et al. (2002) have demonstrated that DAF's effectiveness for cold waters and the use of PACs as an optimal coagulant. This could be very useful for the FCFV industry as wash-water are about 5-10^{o}C (Lehto et al., 2014; Mundi, 2013). DAF systems are applicable for wash-water treatment as they are capable of handling heavy loading of dissolved and particulate matter, utilize lower dosage to achieve higher efficiencies in comparison to settling systems with C&F, and can handle high loading rates.

2.3.7 Electrocoagulation

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 a current to the wastewater, through aluminum or iron electrodes to destabilize its negative charge (coagulation) and allows for the flocculation of the particles. This technology possesses many advantages such as in situ coagulation (no external coagulant chemical required), easy installation, odour and colour removal, lower secondary pollutions, ability to reduce microorganism loadings, and most importantly low residence times (Chopra, 2011; Drogui et al., 2008). Current food-industry wastewater is typically treated with biological treatment, however, the treated effluent does not meet regulatory compliance. Thus, Barrera-Díaz et al. (2006) investigated the use of electrocoagulation and developed a relationship between treatment times and COD removed. Electrocoagulation has also been coupled with adsorption Electrocoagulation's ability to counter many water pollutants make it advantageous to use in minimally processed fresh-cut fruit and vegetable washing and processing industry, but limited studies have been published.

2.3.8 Other Treatments

Other treatments to note and consider are membrane filtration, electro-hydro-cyclone, biological methods (Bioreactors, SBR, and MBR) and bioelectrical systems. None of these were the focus of the proposed work as they lie outside the scope of the work. However, since one of the installations visited had an MBR system, and the potential these technologies have for the treatment of wash-water an overview will be provided on upcoming technologies.

Membrane filtration is often utilized to further clean the water and bring it to a potable standard. Reimann (2002) demonstrated the use of ultra-filtration with reverse osmosis process for treatment of carrot wash-water resulting in treated water meeting the German regulations. Reimann and Kern (2005) looked at the correlation of organic matter in carrot wastewater with membrane efficiency and found a direct correlation. Membrane filtration can also serve as a mechanism to reduce bacterial counts and provide some disinfection to the waters (Van Haute et al., 2015c). Nelson et al. (2007) studied fresh-cut vegetable wastewater for direct application of submersed microfiltration and found that treatment efficiencies were low for solids removal. Thus, it is suggested that membrane filtration is for low contaminated water or as a pre-treatment step before filtration. From these membrane studies, it's evident that the high organic loading in the wash-water require a pre-treatment step which can be achieved by treatment technologies within the proposed research.

Another advanced and emerging technology include electrocoagulation-floatation, which is same as electrocoagulation but also includes a floatation cell to clear the floats (Jiang et al., 2002; Matis and Peleka, 2010). Another innovative technology to handle both liquid and solid waste is called Bioelectrochemical systems (BES). BES encompass a wide group of biologically catalyzed electrochemical systems with different utilities but with a general aim to remove substrates and produce energy. Microbial fuel cells (MFC) are one form of BES which can directly convert the chemical energy from an organic source to electrical energy through a series of redox reactions (Butti et al., 2016; ElMekawy et al., 2014). Potato processing wastewater was assessed for MFC by Durruty et al. (2012) and the study showed that high COD removal, but a low energetic conversion of the organic matter. MFC has recently been developed and research is still in its infancy, thus optimum condition has not yet been derived. These advanced technologies can be utilized in the minimal and fresh-cut fruit and vegetable processing industry as some wash-waters are high in organic loading and would be ideal for MFC.

Membrane bioreactor (MBR) treatment is a well established and maturing technology with many full scale municipal and industrial applications. Membrane filtration is coupled with conventional activated sludge processes to degrade the organic matter and simultaneously filter out the suspended and dissolved solids. The primary purpose is to allow water reuse due to its superior performance in regard to suspended solids, nutrients, heavy metals, and pathogens (Krzeminski et al., 2017; Katsou et al., 2016). Energy consumption and membrane fouling remain two major challenges to widespread adoption. Regardless it has many advantages over conventional treatments, such as small footprint, treated effluent quality comparable to tertiary treatment, automatic operations allow for remote control and monitoring, minimal operator attention, odourless, and silent operation to name a few (Tai et al., 2014). The use of MBR to treat food processing wastewaters has been studied with successful water reuse applications, however, membrane fouling remains a concern (Moore et al., 2016; Jeong et al., 2017; Gómez-López et al., 2017a).

The solids generated from treating wash-waters require disposal as well. Large volumes of solid waste are produced, due to the high level of total solids in wash-waters. Many solutions are available but cost-benefit analysis will always dictate the feasibility of a certain option. Anaerobic digestion, by-product as cattle feed substrate, land application are some of the solutions to handle solids. Anaerobic digestion of fruit and vegetable waste has been explored, studies show that it serves as a consistent, clean and reliable organic waste stream for the digestion process. It has been reported to increase biogas production when used as a substrate (Park et al., 2011). Bouallagui et al. (2009) reported similar findings when fruit and vegetable waste was added as co-digestion waste. Fruit and vegetable waste can also be utilized as bio sorbent for water treatment of industrial and agricultural wastewater and recovery of valuable metal has been highlighted by Patel (2012). Both carrot and potatoes have been investigated to understand their adsorption capacities. Management of solids is outside the scope of this work. However, development of feasible wash-water treatment will consider solid waste volumes as an important factor to consider.

One passive technology to deal with wash-water treatment is wetlands. Wetlands occur naturally but constructed wetlands are manmade designed to handle various types of wastewater for natural attenuation. Constructed wetlands have been around for many decades and have been shown to be effective in handling many different types of wastewater (Vymazal, 2014). Kato et al. (2013) investigated wetlands for cold climate of agri-food industry using a special six multi-stage hybrid wetland systems and effectively was able to reduce the footprint needed to treat high organic loading wastewater. Naz et al. (2009) compared free water surface flow (FWSF) and horizontal subsurface flow (HSSF) constructed wetlands and suggested that HSSF are effective at handling suspended solids and total COD. Wetlands are ideal for wash-water treatment following physio-chemical treatments that will be explored in the proposed work.

2.3.9 Disinfection

Disinfection is a critical final step in fruit and vegetable washing and processing production as it affects the quality, safety and the shelf life of the product (Gil et al., 2009). The main goal of a sanitizer is to reduce cross-contamination. Vegetables and fruits have a high water and nutrient content which promotes bacterial growth and can carry pathogens from the field to washing and processing operations, and end up at the consumer table, if not washed and sanitized adequately (Lehto et al., 2011). It's also important to ensure the packaged product has a suitable shelf live and protect the consumer from any food-borne outbreaks. Most fresh-cut fruit and vegetable are consumed raw and can carry the risk of spreading harmful pathogens to humans. Water disinfection is the final step in water recycling which reduces the risk of disseminating spoilage and pathogenic microbes. It is important to recognize that proper washing and processing actions play an important role in the prevention of transmission of pathogens (Sánchez et al., 2015). E.coli is often used as an indicator pathogen as it provides a general indication of the quality of water used for washing and sanitizing fruits and vegetables. E.coli is also used by regulatory body to assess the quality of the process and wash-waters. However, Salmonella and Listeria are far more prevalent and have been part of recent lettuce and other food borne illnesses and contaminations.

To prevent this from happening, wash-waters are dosed with sanitizers and disinfectants, chlorine is the most commonly used disinfectant in the minimal and fresh-cut fruit and vegetable industry (Casani et al., 2005; Gil et al., 2009; Gómez-López et al., 2013; Haute et al., 2013, 2015a, 2015b, 2015c; Lehto et al., 2014; Sánchez et al., 2015). Chlorine has been used in many industries including the water and wastewater treatment industry as a cost-effective means of reducing and eliminating bacterial and microorganism counts to safe levels for human consumption. For this reason, it has been widely used, is easily accessible, and provides a cost-effective solution at a reasonable price. Chlorine also offers the ability to provide residual disinfection capacity. Other chlorine based sanitizers have also been investigated for minimal and fresh-cut fruit and vegetable washing and processing applications. Pan and Nakano (2014) looked at sodium hypochlorite (NaClO) and chlorine dioxide (ClO_2) with mild heat (50ºC) and has found it effective in reducing pathogen counts (total plate count, coliform count and E. coli O157:H7). Chlorine dioxide (CD or ClO_2) is also a strong oxidizing agent has been known to significantly reduce pathogens in apples and strawberries (Chen et al., 2014). Chlorine demand is a function of pH and organic matter within the wash-waters. Maintaining free chlorine is a challenge when chlorine is first added to water, it is consumed at first by organic matter, bacteria, etc. However, eventually further addition of chlorine will exceed demand and higher levels of chlorine are measured. But this case changes when there is ammonia present in the water, as the chlorine will first bond with ammonia, achieving an ideal state of monochloramine disinfection. Further addition of chlorine continues to bond with ammonia, experiencing dichloramine and trichloramine states, which are not ideal as they reduce the residual chlorine. Thus, the disinfecting power is drastically cut. Only after the point, where fully bonding all the nitrogen from the ammonia with the chlorine, you return to the original curve, where for every part of chlorine added/dosed one will see one part of chlorine residual, a relationship is linear, shown in Figure 2-2.

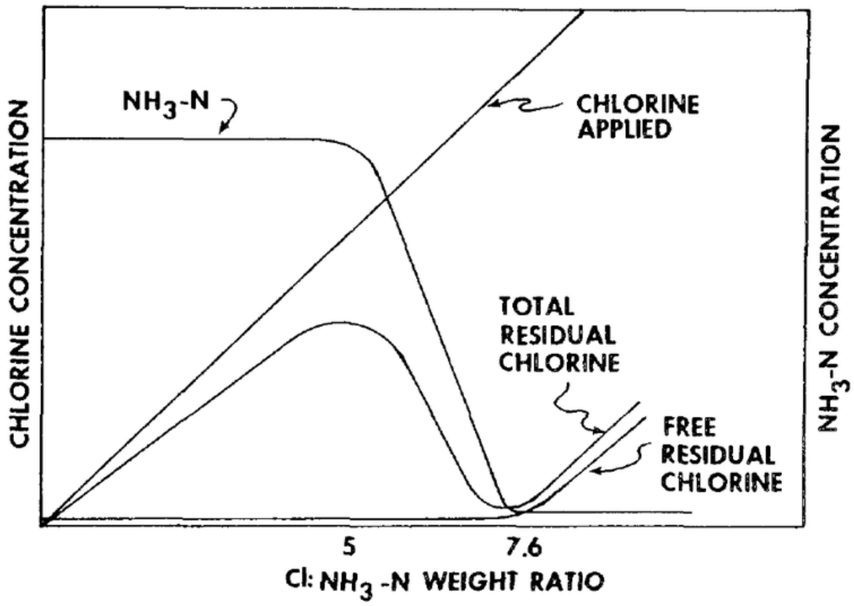

Figure 2-2: The concept of chlorine demand curve is illustrated (Adopted from Orner, 2011).

Recent efforts have been made in reducing its use and to eliminate it as a disinfectant due to concerns associated with the formation of disinfectant by-products (DBPs) (Gómez-López et al., 2013). DBPs are formed with chlorine reacts with natural organic matter within the wash-waters (Ölmez and Kretzschmar, 2009). Organic matter also inhibits disinfection as it takes up much of the free chlorine (Magnone et al., 2013). For these reasons, chlorine is not used in many European countries such as Belgium, Netherlands, Denmark, Switzerland and Germany (Gil et al., 2009).

Recent research in sanitizing fresh-cut produce focus on disinfection methods utilizing non-chlorine solutions. Some potential alternatives for chlorination are ozone, ultraviolet light (UV), organic acids, peracetic acid and hydrogen peroxide, electrolyzed oxidizing water, and advanced oxidation processes (Gil et al., 2009; Ölmez and Kretzschmar, 2009). Potential of electrolyzed water as an alternative disinfectant agent for the minimal and fresh-cut fruit and vegetable washing and processing industry was recently explored by Gil et al. (2015). Van Haute et al. (2015a) explored disinfection of a full scale leafy vegetables washing process with hydrogen peroxide and the use of a commercial metal ion mixture to improve disinfection efficiency. Another effective method includes the use of peroxyacetic acid (PAA), which is cable of inactivating E.Coli in fresh-cut lettuce wash-water without the effects of producing DBPs (Sánchez et al., 2015).

High power ultrasound (HPU) at low frequencies is also an emerging technology for the sanitizing wash-waters for recycling purposes due to its ability to handle changing water quality of wash-waters (Sánchez et al., 2015). Another method of disinfection referred to as neutral electrolyzed water (NEW) was evaluated using carrots in lab and full scale plant by Lee et al. (2014). Results show it was an effective sanitizer, however, a colour change of the product was noticeable. Each approach offers advantages over the other and applications are dependent on the type of FCFV process applied by the washer/processor. However, the importance of reducing particulate and dissolved solids are essential in having a cost-effective disinfection method for minimal and fresh-cut fruit and vegetable washing and processing process water.

The solid reduction method/technologies proposed within this research work will help to reduce the particulate and dissolved matter, as a result, aid tremendously in allowing disinfection methods to sanitize wash-waters effectively.

2.4 Selection of Treatments and Coagulants

Selection of treatments for this study was based on previous use of the treatment technology for typical wastewaters for domestic, municipal, and industrial applications, and for the fruit and vegetable wastewaters, as highlighted above in literature research. In conjunction with the study objectives of solids reduction which are typically achieved by primary wastewater treatment technologies. The treatment selected for bench-scale testing consisted of screening (sieve), hydrocyclone, centrifuge, coagulation and flocculation with settling, gravity settling, dissolved air flotation, and electrocoagulation.

Treatment parameters such as screen size for sieve treatment were based on currently used in screening equipment provided by the manufacturer and available sieve sizes for bench-scale testing. For hydrocyclone, the operating parameters were selected based on the optimal condition for treating wastewater with soils/dirt highlighted by Bain and Morgan (1983), Hwang et al. (2012), Soccol and Botrel (2004), and Yang et al. (2013). Centrifugation parameters were selected utilizing information about full-scale centrifuge treatments, such as the centrifugal forces and treatment time. While the batch treatment containers for centrifugation were determined dependant on the volume of water required for water quality testing, typically about 1 litre for physiochemical and microbiological testing. The process for Jar Test for testing gravity settling and coagulation and flocculation were implemented based on standard testing procedures. The volume and times for rapid mix, slow mix and settling were based on literature and sample volume constraints. A volume of 500 mL per jar was used, due to the large volumes and numbers of testing needed for coagulation and flocculation, as four different coagulants were assessed.

The four different coagulants tested 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. These four coagulants make up of two synthetic and two organic coagulants. The coagulants selected were based on what is currently used in the industry and is also a food grade coagulant, such as Nalco. While others such as Sigma-Aldrich, Chitosan, and Polyglu were used to assess their effectiveness compared to Nalco and to provide a wide variety of chemical for potential considerations.

Dissolved air flotation was selected for its effectiveness to treat waters which contain both solids that settle and float in water. The parameters were optimized in a previous study by Mundi (2013), where the recycle rate, detention, and retention rates were studied for the effective reduction of solids in wash-waters. Similarly, electrocoagulation parameters were selected based optimal design highlighted in literature and what is available for construction of bench-scale setups such as electrical supply, aluminum electrodes/plates, and reactor size. Additional details on setup, equipment, and procedure are highlighted in methods for each part of the study from Chapter 3 to 5.

Treatments were setup in parallel to consider each treatments impact on solids reduction, and to allow comparison between treatments. Treatments were not combined in series and were not optimized for different wash-water as the focus of the study consisted of studying a large variety of fruit and vegetable wash-waters. Although the study was conducted in Ontario, Canada it is still applicable to other parts of the world under the same set of conditions are observed in this study. These include similar growing/harvesting methods, geography (soils), processing equipment, and process/fresh-water quality. As such, the use of developed models will extend beyond Ontario to other parts of the world involved in the processing and washing of fruits and vegetables. The assumptions involved or initial condition that are needed to be met to apply the developed analysis and models are included. These will aid in ensuring the right results are applied to combat and understand wash-water treatment implementation.

2.5 Statistical Analysis and Modelling – MLR and ANN

This section will briefly define the two modelling methods used for developing prediction tools. The two different types of models explored consist of multiple linear regression (MLR) and artificial neural networks (ANN), where MLR utilizes linear or sometimes log functions, while ANN extends these theories to include the uses more complex non-linear functions like tanh. The principles behind each type of modelling and how they work as predictive methods for wash-water treatment selection are presented. The advantages and disadvantages associated with each type of modelling are also highlighted.

Many problems in engineering and science are solved using techniques such as statistical analysis, including MLR, and ANN modelling. These methods have been applied in many different fields, including prediction of water and wastewater treatment applications. Modelling pollution loading in agri-food industries is important for controlling point source pollution, and to predict effluent water quality of wash-water treatment and reuse. We know this is possible as many studies have successfully shown that utilizing wastewater quality and treatment operation parameters to model effluent water quality parameters can lead to many useful tools. Which can aid in assessing the effectiveness of treatment and give an indication of treatment for implementation?

Studies in the literature have demonstrated the successful use of MLR and ANN methods as a vital tool in predicting water quality of wastewater from different sectors. Obaid et al. (2015) used MLR methods to model BOD and TSS parameters of municipal wastewater during the festival and rainy days. Tomperi et al. (2017) modelled paper and pulp effluent, more specifically the aeration tank of full scale activated sludge plant treatment efficiency and quality of effluent by using optical data correlated to water quality parameters (TSS, BOD, COD, TN, and TP). Results showed successful use of only optical properties to estimate effluent water quality parameters, with R^2 ranging from 43 % to 78 %. Many growing cities under development suffer from elevated rates of soil erosion from land clearing and grading activates, as such must contain the soil erosion using construction site ponds. Trenouth and Gharabaghi (2015) successfully modelled the loss of soils from construction sites using MLR and ANN techniques. Atieh et al (2015) highlighted the use of ANN models for prediction of sediment rating curve parameters for ungauged streams. Li et al (2015) used ANN to model the removal of TP using influent TP concentration, water temperature, flow rate, and porosity. Khambete and Christian (2014) utilized ANN for estimating sewage treatment plant effluent BOD. For specific treatments, Zhao et al (2014) assessed electrocoagulation treatment efficiency from hardness, COD, and turbidity, and a final example of ANN application is from Asnaashari et al. (2013) for predefining water main failures.

Comparison of predicted parameters between MLR and ANN models is common, as mentioned in the above studies. This is done to ensure findings through different prediction methods reach a similar conclusion and to validate the finding of MLR, and to improve predictive models by increasing accuracy through ANN techniques. The ANN models are more powerful in comparison to MLR models as they can find complex patterns in datasets which are not easily described by a set of MLR equations. ANN utilize advanced nonlinear functions in comparison to MLR techniques which are linear. However, ANN models require a much larger dataset in comparison to MLR. Prediction of BOD and COD from TSS, TS, pH and temperature using MLR and ANN methods were highlighted by Abyaneh (2014) and Verma and Singh (2013) have demonstrated ANN as superior to MLR in some cases. More specific application in the field of fruit and vegetable science include prediction of kiwifruit firmness (Torkashvand et al., 2017), treatment of potato wash-water (Bosak et al., 2017), and predicting chlorine demand of fresh and fresh-cut produce based on produce the properties of wash water (Chen and Hung, 2016).

Before modelling the data is checked for errors, outliers, and invalid data entries to ensure proper usability for modelling. Selection of input variables used to predict selected output is very important. Too many input variables can increase computation requirements, make it less practical, lead to overfitting, and increase the cost of collecting and analyzing extra input variables. Variable selection is done using common sense knowledge of correlating variables in addition to checking correlation using statistical analysis such as using correlation matrix analysis, to check for statistically significant variables (p-value < 0.01). Starting with correlation analysis one can determine the number of input variables for MLR or ANN models. Scaling or normalizing of input variables is often done to reduce unintended influencing of the weights occurring due to the different magnitudes of input variables used, for example, TP (in the range of hundreds) versus TSS (in the range of 10 thousand).

MLR is defined as a statistical technique used in modelling two or more explanatory variables (independent) and a response variable (dependent) by deriving a linear equation into the observed data. The simplest form of linear regression is given by the classic, y = mx + b equation, where the dependent variable y can be modelled from a known independent variable x, given the linear trend as provided by slope and intercept from the plotted data. For multiple independent variables the MLR is mathematically stated using the following notations: y_i is the dependent variable, β_0 is a constant or intercept, $x_{i,k}$ is an independent variable, β_k is the coefficient regression vector or slope, and ε_i is a random measured erroa r. The interaction of all variables are shown in Eq. (2). The MLR analysis was conducted using open source r language (RStudio - Version 1.0.153)

$$y_i = \beta_0 + \beta_1 x_{i,1} + \beta_2 x_{i,2} + \cdots + \beta_k x_{i,k} + \varepsilon_i \tag{2}$$

ANN, on the other hand, is based on biological systems, more specifically a brain neuron, which is referred to as a perceptron as highlighted in Figure 2-1 as a circle under the hidden layer. Like the brain, ANN has multiple inputs from which it can predict an output, but only after sufficient training has taken place. The mathematical expression of a perceptron is given by, $x_o = f_o(\sum_{inputs:i} w_i x_i)$, where, the output x_o is determined from inputs x_i, by using the activation function f_o. The w_i variables are the weights, which the ANN learns/estimates from the training data set. The neuron is analogous to three common statistical models: multiple linear regression, $y = \sum_i w_i x_i$ where the f_o is the identity function with an attached weight/bias/intercept given as $f(x) = x + \theta$, second, logistic regression, and finally the linear discriminant analysis used for binary responses (0,1). The feed-forward neural network with one hidden layer and one neuron is the most common choice for regression-like modelling applications, as shown in Figure 2-1.

In this study, the ANN utilizes a large number of inputs (process, product, treatment, and influent water quality parameters) to neurons, which perform calculations using weights to produce an output/results. A schematic of the ANN structure is presented in Figure 2-1, the three main components are highlighted: the input layer (input variables), hidden layer (neurons), and an output layer. The connection line used to connect the input layer nodes to hidden layer nodes has an associated weight, which highlights the importance of each input variable.

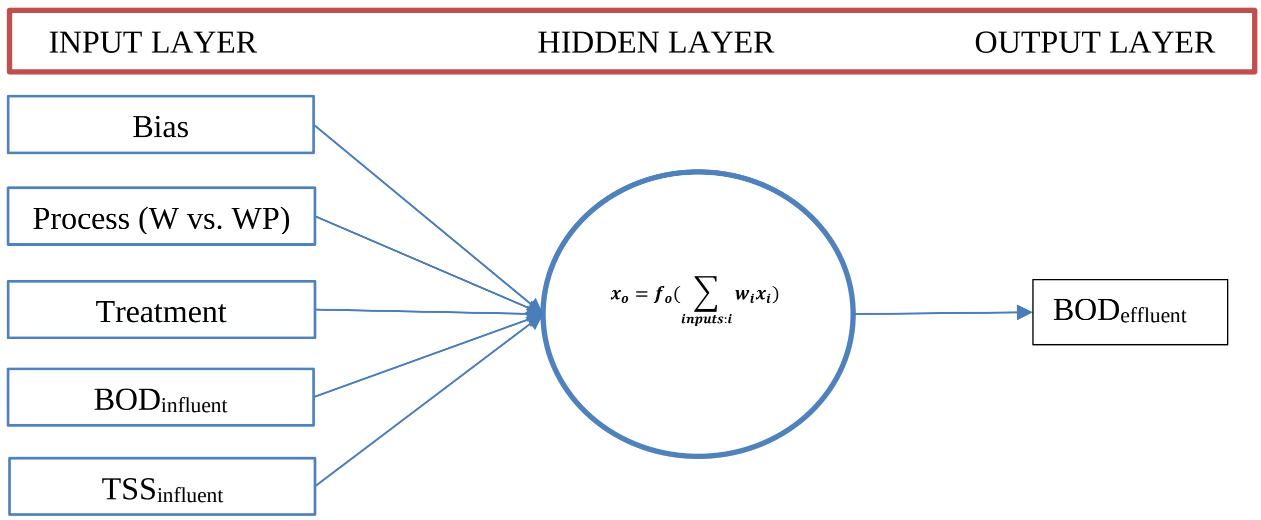

Figure 2-3: Example configuration of an ANN model shows the three main parts of the process, input, hidden, and output layer. The configuration consists of 5 inputs, one neuron/preceptron, and a single output.

Training of ANN models is essential before they can be used to perform predictions on future events/samples. During training, the weights used to assess the inputs to generate an output, are optimized to reduce the error between actual and predicted output. The weights are validated through a testing process. The development of ANN models was done using Tiberius – Predictive Modelling Software (www.philbrierley.com), which is an opensource, limited functionality, inexpensive, and highly user-friendly ANN program that utilizes the multilayer perceptron (MLP) methodology. The algorithm consists of two steps, first the forward pass, where the predicted outputs corresponding to the given inputs are assessed. In the second step, the backward pass, the partial derivatives are propagated back through the network. This combined process is used to minimize error or optimize the gradient descent algorithm by adjusting the weight for each input, the whole process is iterated until the weights have converged. For this study, 70 percent of the dataset was randomly selected for training and testing while the rest 30 percent was used for validation (Gazendam et al., 2016).

MLR models have been utilized for decades to predict linearly correlated parameters. They are easy to understand and can easily be highlighted in a mathematical equation. Meanwhile, ANN models are very powerful models that utilize the activation function which is non-linear, where the weights of the parameters are highlighted but not the function themselves. However, they also require large data sets. Exploring both methods can confirm core findings and provide a suitable model based on application.

2.6 Regulations

Effluent (treated/non-treated) from operations need to meet disposal limits as set by the governing bodies. The challenge lies in identifying the appropriate governing bodies and the prescribed limits that need to be met. This is because management of solids and liquid waste product on farms and for washing/processing operations are governed by three different Regulations; the Nutrient Management Act, Environmental Protection Act and/or the Ontario Water Resources Act. In addition to municipality/city by-laws. The option of land application of liquid and solid waste, referred to as Non-Agriculture Source Materials (NASM) are regulated under the Nutrient Management Act and its regulations (OMAFRA, 2016). Anaerobic digestion and composting of vegetable waste are possible solutions to address the concentrated solids, which are generated from wash-water treatment and reuse (Emily, 2013).

EPA titled report 2012 Guidelines to Water Reuse is a good resource to understand water reuse and management (US Environmental Protection Agency, 2012). This extensive report details various water reuse regulations, technologies, and case studies within the U.S.A. and the world. The report also sheds light on industrial reuse applications involving vegetable processing wastewaters, but it fails to list water quality criteria requirements, which is significant to minimal and fresh-cut fruit and vegetable washing and processing industry. German legislation provides specific guidelines for discharge limits on wash-water produced from fruit, vegetable, and potato processing industry. These limits are for releasing wash-water to open waters such as streams, rivers, and lakes. The regulated parameters are listed in Table 2-1, below (Federal Law Gazzete, 2004).

Table 2-1: German regulation limits for disposal of fruit and vegetable production wastewaters

	Qualified random sample or 2-hour composite sample (mg/l)
5-day biochemical oxygen demand (BOD5)	25
Chemical oxygen demand (COD)	110
Ammonia nitrogen (NH_4-N)	10
Total nitrogen as the sum of ammonia, nitrite and nitrate nitrogen (N_{tot})	18
Total phosphorous	2

Current regulations in Ontario do not directly address fresh-cut fruit and vegetable producers (washers) and processors, however, the limits listed in Table 2-2 serve as guidelines deemed safe by the three levels of governments. The limits for drinking water have been set by the Ministry of the Environment and Climate Change (MOECC) and is followed throughout the province. The guidelines for sanitary and combined sewer discharge are set by municipal governments and vary from one municipality to another. It also needs to be emphasized, that wastewater discharged to the sewer system undergoes further treatment by the municipal wastewater treatment plant, hence the higher levels. For rural producers, discharge to the surface waters will fall under the provincial water quality objectives. The actual limits depend on site location and effluent characteristics. It needs to be stressed, that the limits mentioned herein serve only as a reference and are not to be used for regulatory compliance.

The Canadian Government has very specific regulations governing fresh fruit and vegetable titled Fresh fruit and vegetable regulations (Minister of Justice, 2012). This document has outlined the grades of water that can be used for processing and where water reuse is permitted, i.e., the use of potable water for final rinsing. It is also stated that non-potable water may be used for washing of soil from raw produce but with some constraints, which are not clarified (Minister of Justice, 2012). This document can aid in determining where to reuse wash-waters with or without treatment and what is currently allowed in terms of the standard of process water.

Table 2-2: Table showing prescribed limits of the listed parameters set by the provincial, municipal, and federal governments

Parameter	Target concentration for drinking water[1] (mg/L or ppm)	Target concentration for sanitary and combined sewer discharge[1] (mg/L or ppm)	Provincial Water Quality Objectives[3] (mg/L or ppm)
Ammonia as N			0.02*
Nitrate as N	10		
Nitrite as N	1		
TKN		100	
Organic Nitrogen (TKN – Ammonia as N)	0.15		
Total Phosphorus	0.01	10	0.02
Zinc	5	2	0.03
Copper	1	2	0.05
Manganese	0.05	5	
Iron	0.3		0.3
Molybdenum		5	0.01
Boron	5		2
Chloride	250		
Sulphate	500		
pH (Log_{10} [H^+])	6.5 – 8.5		6.5 - 8.5
Potassium			
BOD		300	20[a]
COD			
TSS		350	25[a]
TDS	500		
Turbidity (NTU)	5		
Pathogens	not detectable		400 per 100 mL[a]
Hardness	80 – 100		
*Fats, Oil and Grease	Site specific	150	

Data obtained from Supporting Document for Ontario Drinking water Quality Standards, Objectives and Guidelines, Tables 1, 2, and 4

[2] Data obtained from the City of Toronto Sewer Discharge and Storm water Discharge Limits, Table 1

[3] Data obtained from Provincial Water Quality Objectives for Surface Water, some parameter are subjected to additional conditions

* See additional comments regarding parameter measurement in reference documents

[a] Limits for effluent discharged to receiving waters; Guidelines for Effluent Quality and Wastewater Treatment at Federal Establishments

The requirement of water quality for reusing wash-waters depends on many factors, such as the quality of water and volumes needed, for what purpose – washing, processing, or sanitizing produce, level of treatment technology implemented. Quality of waters needed to depend on the type of fruit or vegetable washed or processed, for example washing root-vegetable wash-water are often recirculated with a dunk tank and disposed of at the end of the washing cycle, as they contain soils and other suspended solids. While sanitization or final rinse in root-vegetable washing require waters that are chlorinated to provide microbial control, which can be reused in the initial washing stages like dunk tanks and rotating washers for root-vegetables. The wash-waters for initial stages of washing don't need to conform to any strict regulations or water quality standards as long as the final stage of washing consist of rinsing with chlorinated waters that provide sufficient microbial control.

Large and small volumes of wash-water are managed differently, smaller volumes produce concentrated streams which are harder to recycle, while larger volumes provide higher dilutions and lower contamination which may be easier to recycle. The level of treatment implemented can dictate the quality of water that will be produced for reuse, for example, primary treatments used for solids reduction will produce water that may only be recycled in the initial stages of washing root-vegetables. While secondary treatments targeting BOD, TN, and TP produce water that may be mixed with fresh-water to achieve drinking water standards. However, the best quality waters are achieved through the use of tertiary treatments and adequate disinfection, which can be used for final rinse water as they often meet drinking water standards, for example, membrane bioreactor with UV disinfection. Also, the length of washing period and the amount of product requiring washing will also dictate the volume of wash-waters generated and whether there is sufficient need to recycle waters or not since the operating period may be few days to few weeks.

2.7 Literature Review Summary

The completed literature review shows that some characterization studies have been conducted but do not cover all types of wash-waters, such as sweet potato and ginseng to name few. Studies showed that minimal and fresh-cut fruit and vegetable washing and processing industries can produce wash-water with high organic dissolved and particulate matter along with high levels of BOD and nutrients (TN an TP) (Casani et al., 2005; Chambers and Zall, 1979; Hafez, A., Khedr, M., Gadallah, 2007; Hamilton et al., 2006; Kern et al., 2006; Lehto et al., 2014, 2009; Safferman et al., 2007; USEPA, 1977).

The key drivers behind these studies were to reduce process water and assess effective treatment of wash-water and the potential reuse of it. Hamilton et al. (2006) from Australia assessed carrot wash-water for reuse potential and reported the high concentration of agrochemicals (chlorpyriphos and linuron) and high levels of turbidity make it non-suitable as irrigation water, however, suggested irrigating carrot would still be fine given no adverse impacts were reported. Hamilton et al. (2006) also noted the high risk associated with wash-water reuse due to high levels of E.Coli present. However, the use of chlorinated water in the final stages of washing carrots substantially reduces this risk. Lehto et al. (2014 & 2009) from Finland looked at carrot and potato wastewater and suggests separation of soil washing from peeling stages, as 90% of the organic loading is from peeling and processing stages. These findings are in line with Mundi's (2013) report on carrot wash-water analysis and treatment. Lehto et al. (2014) and Van Haute et al. (2015a, 2015b, 2015c) demonstrated the use of coagulants to increase solid reduction efficiency of settling basins and reduce chlorine demand, respectively. Kern et al. (2006) in Germany utilized the use of settling basins and wetlands to treat carrot wash-waters, however dissolved solids were not effectively removed and thus reduced treatment efficiency of wetlands.

All the above-mentioned studies have highlighted the challenges in reusing wash-water. Which stems from the fact that wash-waters are high in organic matter along with inorganics originating from soil washing process, particularly dissolved solids which do not settle easily. In addition to dealing with pathogens both of fecal, soil and plant origins. Thus, the goal of any treatment system should be to effectively remove these particles and inactivate targeted pathogens. Conventional treatments such as settling basins are used to treat wash-waters. Although effective in removing particulate matter they are still not able to meet regulatory limits in many cases. The purposed work was initiated to address the limited knowledge on characterization and effective wash-water treatment methods.

Use of chemical precipitation along with other conventional and advanced treatment technologies can allow for rapid/safer water reuse and thus must be investigated further for wash-waters. The Ontario context of wash-water characterization and treatment methods that are cost effective and meet regulatory compliance need to be investigated and therefore is the goal of this research. The proposed work will assess water quality characteristics, study current minimal and fresh-cut fruit and vegetable washing and processing wash-water treatment technologies implemented in Ontario, and test bench-scale treatments to assess effective solids removal (with and without coagulant use). Case per case investigation of wash-water treatment can be costly and implausible. Thus, representative wash-waters from various fruit and vegetable washing and processing facilities are to be collected to get a comparative assessment on water quality parameters and bench-scale treatment testing. These results can give a good indication in terms of which treatment process can be utilized for which wash-waters (Decision Matrix) and how efficient are the selected treatments under study. These consist of Screening, Hydrocyclone, Settling with C&F, DAF, Centrifuge, and Electrocoagulation.

The comprehensive study will generate large sets of data which can be utilized by computer modelling techniques such as MLR and ANN to allow for better prediction and correlation findings. The major outcome of the research is a decision-making tool which has been limited and is suggested to be the next step in addressing wash-water reuse. (Lehto et al., 2014 & Hamilton et al., 2006). Overall study findings can be utilized by industry, government, producers, and processors to put in place best practices for wash-water treatment. However, the findings are most vital to growers who do not know which treatment technology to select, making it a challenging to implement effective treatment, thus, justifying the need for completing the study.

Chapter 3: Fruit and vegetable wash-water characterization, treatment feasibility study and decision matrices

Chapter 3 shows data on different fruit and vegetable washing and processing operations from Southern Ontario were collected to determine water quality characteristics and process/operational parameters. A total of 83 samples were collected from different wash-water operations, consisting 7 samples of tree fruit (Apple), 55 samples of root vegetables (Ginseng, Potato, Sweet Potato, and Carrot), 3 samples of leafy greens (Spinach), and 18 samples of mixed (mixture of root vegetables, tree fruit, and leafy greens). Bench-scale testing allowed for the development of table-based treatment selection tools. A treatment feasibility rating can be obtained from tables by looking up treatment, wash-water, and process type. The rating systems highlights reduction efficiency of wastewater contaminants and 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). Ultimately, we demonstrate that the methodology allows quick look-up of feasible treatments based on product and process, which has not been done before for fruit and vegetable washing and processing industry. The work was submitted and published in the peer-reviewed, Canadian Journal of Civil Engineering and is cited as follows:

- *Mundi, G. S., Zytner, R. G., & Warriner, K. (2017). Fruit and vegetable wash-water characterization, treatment feasibility study and decision matrices. Canadian Journal of Civil Engineering, 11(44), 971–983.*

Note: In Chapter 3, EC is used as an acronym for Electrocoagulation and, similarly CV for the coefficient of variation. While Chapter 4 EC is used for electrical conductivity and CV for the confidence interval, this was due to journal formatting and editor's request. Table 3-2

3.1 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 consumer's 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 m3 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 within 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. 2006 and2007; 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; Nemeth, D., Shortt, R., & Brook, T., 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 the 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 worldwide. As such, research efforts are needed to explore the 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 treating the wash-water they generate.

3.2 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 (Nemeth, D., Shortt, R., & Brook, T., 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 behaviour 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 electrocoagulation.

3.2.1 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).

3.2.2 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). The 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).

3.2.3 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).

3.2.4 Coagulation and Flocculation Process (C&F)

C&F is widely used in the wastewater and food industry to precipitate out a particulate and dissolved matter (Hafez et al. 2007; Van Haute et al. 2015c). 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. 2015c; 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).

3.2.5 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.

3.2.6 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.

3.2.7 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).

3.3 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 3-1. 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 3-1 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 the 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 the laboratory refrigerator, set at 4 °C until use for testing.

Table 3-1: 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**

3.3.1 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 3-1 for a process flow diagram of the study. Table 3-2 shows the water quality parameters that highlight the physical, chemical, biological and microbiological properties of the wash-water. Table 3-2 also shows abbreviated names of water quality parameters which will be used from here on, 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).

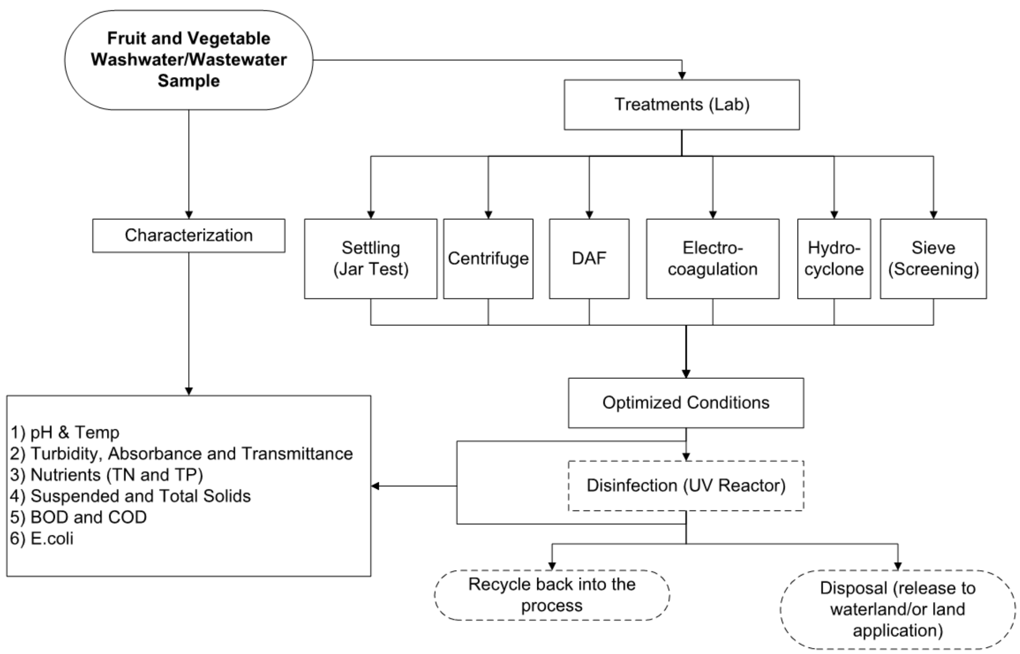

Figure 3-1: Process Flow Diagram of Wash-water Bench-scale Treatment Testing

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 the formula, $((C_i-C_f)/C_i) * 100$, 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 were based on current methods used in the industry. The screening was assessed through batch tests, by pouring 500 mL of the wash-water sample onto a standard soil sieve of 100 µm size, placed on top of a 1 L glass beaker. Clarified samples were assessed for appropriate parameters. The test was used to understand the reduction in solids from a screening of wash-waters. The hydrocyclone experiment used approximately 4 L of well-mixed wash-water sample pumped at a flow rate of 1.3 L/min to a 48 mm diameter of acrylic polymer 3D 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 an 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 the 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 100 mL reactor, which was later improved to 500 mL reactor to process a 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 direct current (DC). 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/m^3 for the small and the large setup, respectively. Upon completion of the experiment, the clarified water was decanted and analyzed for water quality parameters.

3.4 Results and Discussion

3.4.1 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 3-1.

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 are 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 3-2.

Table 3-2: Range of Raw Wash-water Quality Parameters of Trees 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)

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 3-1.

Water quality parameters of tree fruit wash-waters were highly variable as shown in Table 3-2. 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 3-2 shows that root crops have high levels of SS, while tree fruit, leafy greens and mixed wash-waters were higher in DS. SS is much easier to treat as they settle out faster in settling ponds/tanks compared to DS. TS is generally higher for root crops due to soils, loose root materials, or waste 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 the 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 a 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 the 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 is 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 3-2 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.

3.4.2 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 is highlighted in Table 3-3.

Table 3-3: 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).

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 3-3, 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 the percentage of organic and inorganic matter, dissolved and suspended matter.

Assessment of on-site treatment systems, as highlighted in Table 3-3, 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.

3.4.3 Bench-Scale Treatment Assessments

The 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 the 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 the 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.

3.4.3.1 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 3-4. 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 a 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).

Table 3-4: 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										

3.4.3.2 Hydrocyclone

Hydrocyclone testing worked well with high levels of solids containing sand, but poorly with other types of wash-waters. As seen in Table 3-5, 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 a good reduction in turbidity, this is due to a 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 is not suitable for hydrocyclones.

Table 3-5: 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												

3.4.3.3 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 3-6. 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 a 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.

Table 3-6: 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														

3.4.3.4 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 3-7 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 a 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.

Table 3-7: Settling Without any Chemical Aid, Natural Settling Results of 14 different Wash-waters

Facility	**A1 (F1, F2, & F3)***	**A2**	**C2**	**G1**	**G2**	**LG1**	**MV 1**	**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

3.4.3.5 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 3-8, 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 3-8. 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. 2015c).

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 used. 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.

Table 3-8: 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 - $FeCl_3 \cdot 6H_2O$.

3.4.3.6 Dissolved Air Flotation

DAF treatment showed promising results as seen in Table 3-9. DAF could 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 facilities with both washing and processing stages. COD seemed to be well reduced for all wash-waters due to 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. The treatment worked well on most wash-waters except for wash-water involving processing (A2, LG1, MV1, P3).

Table 3-9: DAF Treatment Results of 13 different Facilities

Facility	**A2**	**C2**	**G1**	**G2**	**LG1**	**MV 1**	**P1**	**P2**	**P3**	**SP1**	**SP2**	**C1**	**MV 2**
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													

3.4.3.7 Electrocoagulation

EC provides very high levels of treatment as the electrical charge ensures effective COD, BOD, and pathogen reduction, in addition to providing a C&F effect for solids reduction. It is true that EC is effective at removing solids/colloidal matter, however, the cause of the 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 3-10 shows that EC was highly effective on SP2 and G2, wash-waters that had very high levels of soils. More testing is needed with electrocoagulation, as only a 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 a 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.

Table 3-10: 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.

3.4.4 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 3-11, 3-12, 3-13 and 3-14 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).

Table 3-11: 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														

Treatment effectiveness for solids reduction is highlighted in Table 3-11. 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, 2015a). 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 3-12: 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 3-12 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 3-13: Decision Matrix for Bench-scale Treatment Performance for Reducing TN & TP 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 3-13 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 3-13 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 is a viable method to reduce TN and TP in wash-waters, due to use of chemicals. Table 3-14, highlights pathogen reduction, which was surprisingly high yet plausible since most bench-scale treatments could reduce high levels of SS. As SS has the potential to trap and hide a significant number of pathogens.

Table 3-14: 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

Developing the decision matrices provided in Tables 3-11 to 3-14 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 into Phase 3 of the study which uses neural network analysis to develop a predictive model for wash-water treatment options.

3.5 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 of 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 the 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 the literature.

3.6 Acknowledgement

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Chapter 4: Predicting Fruit and Vegetable Processing Wash-water Quality

Chapter 4 highlights novel Power-Rank models for estimating wash-water quality. Using the additional data available from OMAFRA, the characteristic dataset was expanded. This is done to broaden the data on characterization in Chapter 3 so a meta-analysis can be completed. The meta-analysis combined all the data in Power-Rank models that can be used to determine the average and standard deviation of water quality parameters, such as TSS, TDS, TS, TP, TN, BOD, COD, NH_4-N, and electrical conductivity. The Power-Rank models can be used to estimate raw wash-water quality parameters for assessing the impact and the level of treatment to meet disposal or reuse requirements. The work was submitted and published in the peer-reviewed, *Water Science and Technology* and is cited as follows:

- *Mundi, G. S., Zytner, R. G., Warriner, K., & Gharabaghi, B. (2018). Predicting Fruit and Vegetable Processing Wash-water Quality. Water Science and Technology. Available online 8 March 2018, wst2018109, DOI: 10.2166/wst.2018.109*

Note: In Chapter 3, EC is used as an acronym for Electrocoagulation and, similarly CV for the coefficient of variation. While in Chapter 4 EC is used for electrical conductivity and CV for the confidence interval, this was due to journal formatting and editor's request.

4.1 Introduction

The fresh produce industry is a heavy user of water, and also produces large quantities of wastewater of varying characteristics with respect to solids content, biochemical oxygen demand, nutrients, and pathogens (Gil et al. 2009; Lehto et al. (2009, 2014); Castro-Ibáñez et al 2017). The untreated wastewater can be detrimental to soils, rivers, and lakes if not treated adequately, due to the high levels of organic matter and solids it contains (Kern et al. 2006; Meneses et al. 2017). There is a diverse range of fresh produce types and it follows that the wastewater characteristics are highly variable (Lehto et al. 2011; Mundi et al. 2017). Some wastewaters are compatible with biological treatments while others with chemical and/or physical treatments. Many challenges exist in determining suitable treatment technologies and the degree of treatment required, as one treatment solution does not fit all (Lehto et al. 2014; Mundi & Zytner (2015, 2017)). Literature shows limited information on detailed characteristics of wastewaters from diverse fruit and vegetable washing and processing operations.

Post-harvest washing and processing of fruits and vegetables require large volumes of water, which produce an equivalent amount of wastewater (Casani et al. 2005). Simple washing in comparison to washing with peeling of root vegetables use up to 3.0 m3 and 5.0 m3 of water per tonne of product, respectively (Lehto et al. 2014). In comparison, this metric varies for facilities in Ontario, as two main types of operations are encountered. Such as the continuous washing (continuous flows producing large volumes) versus dunk tank washing (batch process with small volumes). In addition, operation type and sizing, unit processes, and water efficiency practices have a major impact on water usage and wastewater production, as such water usage can range from 2.7 to 20 m3 per tonne of product processed. In comparison, the dunk tank washing requires as little as 0.6 m3 per tonne of product. The different unit processes can consist of mechanical soil removal, washing, and processing (cutting, budding, and peeling), in addition to cooling and packaging (Lehto et al. 2009). The different unit processes employed at each facility depend on many factors, such as the type of product being washed, fruit or vegetable, and whether it is a root vegetable or leafy green. Water is also used for in-place cleaning of the machinery and floor area.

Food safety and quality are essential for fresh produce processing and can impact the product while in storage, in transit, or on store shelves (Gil et al. 2009). The process water has the potential to carry over pathogens, spoilage microbes, and pesticides during washing processes if not sanitized adequately (Griffith et al. 2015; Van Haute et al. 2015b, 2015c). The generated wastewater, or typically referred to as wash-water is a function of processing and product type (fruit or vegetable). Wash-water characteristics include heavy loads of solids, organic matter, oxygen demand, nutrients, pathogens, and spoilage microbes (Casani et al. 2005; Kern et al. 2006; Mundi 2013; Lehto et al. 2014; Mundi & Zytner 2017). High organic matter and solids make it a challenge to treat the wash-water, especially from peeling of root vegetables (Lehto et al. 2009). Thus, treatment of wash-water is necessary to reduce contaminants and allow wash-water to meet effluent requirements as set by government agencies to safeguard watersheds, environments, and ecosystems (Michalak et al. 2013; Schoen et al. 2017).

Increased demand in combination with changing climate requires resilient management of water resources, such as wash-water treatment and reuse (Bhupathiraju & Tucker 2011; Manzocco et al. 2015; Li et al. 2016). The focus of recent studies has been to improve water management by reducing process water and assess effective treatment of wash-water for potential reuse applications while maintaining the highest food safety (Ivey & Miller 2013; Gómez-López et al. 2017b; Lehto et al. 2017). The key drivers behind these studies the more stringent standards coupled with an increase in fines, including closure due to non-compliance. Castro-Ibáñez et al. (2017), Gil et al. (2009), Lehto et al. (2009, 2011, 2014, 2017) have completed studies, which provide excellent detail on characterization, in addition to treatment feasibility. This study will build on existing research and extend the characteristics of wash-waters to tree fruit and above ground vegetables, in addition to summarizing industry-wide wastewater quality information into simple models. The goal of the study is to develop power regression models that are easy to understand, implement, and are insightful. Which can then be used by stakeholders to understand the level of contamination in wastewater to addresses treatment, disposal, or reuse.

4.2 Materials and methods

4.2.1 Data Collection

Wash-waters from different fruit and vegetable washing and processing operations, see Table 4-1, were assessed for nine water quality parameters: total solids (TS), total suspended solids, TSS, total dissolved solids (TDS), electrical conductivity (EC), chemical oxygen demand (COD), biochemical oxygen demand (BOD), total phosphorus (TP), total nitrogen (TN), and ammonia (NH_4-N). All water quality parameters are measured in milligrams per litre [mg/L] except for electrical conductivity, which is measured in microsiemens per centimetre [µS/cm]. Statistical analysis of water quality parameters was conducted to derive statistical inference properties (mean, standard deviations and variance), to assess probability functions (distribution fits), and to derive equations for predicting raw wash-water quality parameters mentioned above.

Table 4-1: Fruit and Vegetable wash-waters assessed to formulate Power-Rank models for predicting water quality parameters

Product Type and Name	Washing	Washing and Processing	Grand Total
Above Ground			
Broccoli	1		1
Melons	2		2
Mushroom	7		7
Peppers	4		4
Snap Beans	3		3
Squash/Sweet Potato	2		2
Sweet corn	1		1
Tomato	7		7
Zucchini	2		2
Above Ground Total	**29**		**29**
Leafy Green			
Boston Lettuce	2		2
Spinach	3		3
Leafy Green Total	**5**		**5**
Root Vegetable			
Carrot	28	50	78
Ginseng	11		11
Ginseng Seed	4		4
Green Onion	1		1
Mixed	3	9	12
Potato	35	3	38
Pumpkin/Gourd	9		9
Sweet Potato	25		31
Root Vegetable Total	**116**	**62**	**184**
Tree Fruit			
Apple	12	13	25
Sour Cherry	2		2
Tree Fruit Total	**14**	**13**	**27**
Grand Total	**164**	**75**	**239**

A total of 239 samples were obtained, 164 on just washing and 75 on washing and processing, see Table 4-1. All wash-water samples were categorized as either (1) washing, just removing the soil or washing the product to ensure microbiological safety of the food for consumption, or (2) washing and processing wash-waters, where facilities part-take in both, washing the soils off, and cutting and peeling the product, i.e., carrots, and potatoes. These samples were used to assess water quality parameters of the washing and processing wash-waters, this consisted of wash-waters from 21 different types of fruits and vegetables, see Table 4-2 and 4-4. The full dataset consists of 4 subsets, (1) Dataset#1 – 2013 to 2015 from Mundi et al. 2017 (most recent), (2) Dataset#2 –

2011 to 2013 from Mundi et al. 2015, (3) Dataset#3 – 2012 to 2013 from Ontario Ministry of Agriculture Food and Rural Affairs (OMAFRA) and (4) Dataset#4 – 2004 to 2005 from OMAFRA. Wash-water data on water quality parameters were concatenated into one dataset from the four datasets mentioned above. Standard methods for conducting water quality testing were employed to test wash-water samples, Method 2540 (TSS and TS) and Method 5210 (BOD) (Standard Methods for the Examination of Water and Wastewater 2012). Additional testing was done by Hach instrumentation (DR5000-03) using water quality testing kits, for COD, TN, TP, and NH_4-N (TNT821,826,843,830) (Hamilton et al. 2006). The electrical conductivity was measured using Zetasizer Nano-Z (Malvern, ZEN2600, Made in the UK).

4.2.2 Data Analysis

Discrepancies and outliers in the data were assessed by calculating mean, minimum, and maximum of each water quality parameter. Pivot tables were prepared for average and standard deviation values of different products (apple, carrot, etc.) for the different wash-waters types to help develop Power-Rank models. Statistical and engineering analysis was required to understand the distribution fits (normal, log, etc.) of the water quality data. This is useful in determining the level of treatment required to meet effluent regulatory compliance at a certain confidence interval (CI), i.e., 95% or lower. Figure 1 shows the process flow used to understand the level of treatment needed for each water quality parameter.

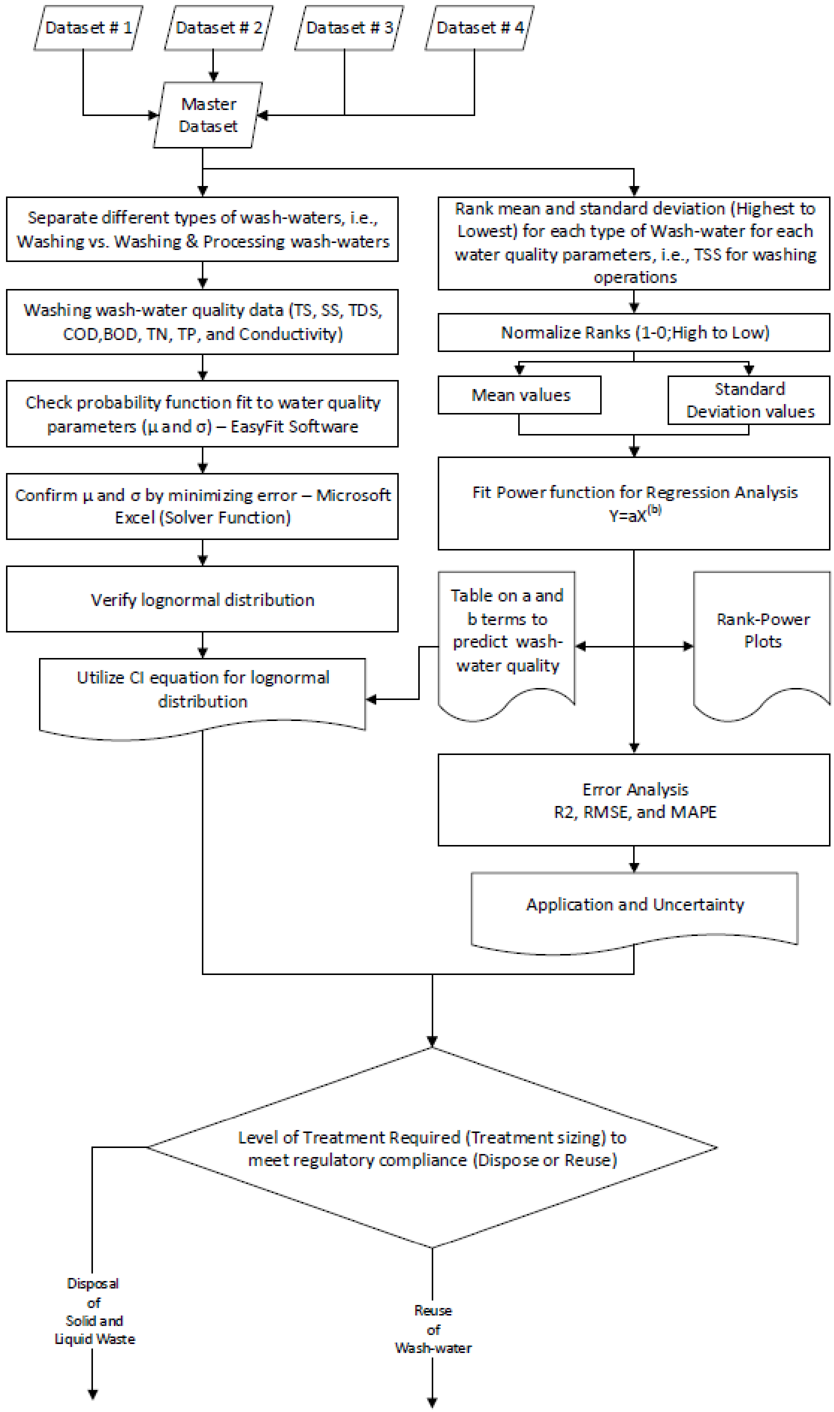

Figure 4-1: Process flow diagram of the analysis performed

The first step was to assess for probability distribution fit, for example, of all TSS values for Potato wash-water. This was done by importing data into EasyFit distribution fitting software (Mathwave, Technologies) to assess the fit under one of the 57 available probability functions within the software. The Kolmogorov-Smirnov (KS) goodness-of-fit test was used to rank the 57 probability functions to determine which one best describes the different water quality parameters. The KS goodness-of-fit test compares two continuous distributions of the water quality parameters, e.g., TSS, and ranks a distribution based on the distance between the expected (the given probability function) and the observed distribution (TSS water quality parameter) (Massey 1951; Thompson et al. 2016). The two-parameter lognormal distribution was selected as the probability function to represent the water quality parameters as it consistently ranked in the top 21 distributions. For example, TSS and BOD for Potato washing wash-waters were selected to demonstrate the fitting of the lognormal distribution function, see Figure 2(a) and 2(b). Both suspended (TSS) and dissolved (BOD) constituencies were a good fit for the lognormal distribution as shown by TSS and BOD probability of exceedance curves. This was also the case with the washing and processing wash-waters for potato product. However, these were not highlighted in Figure 2.

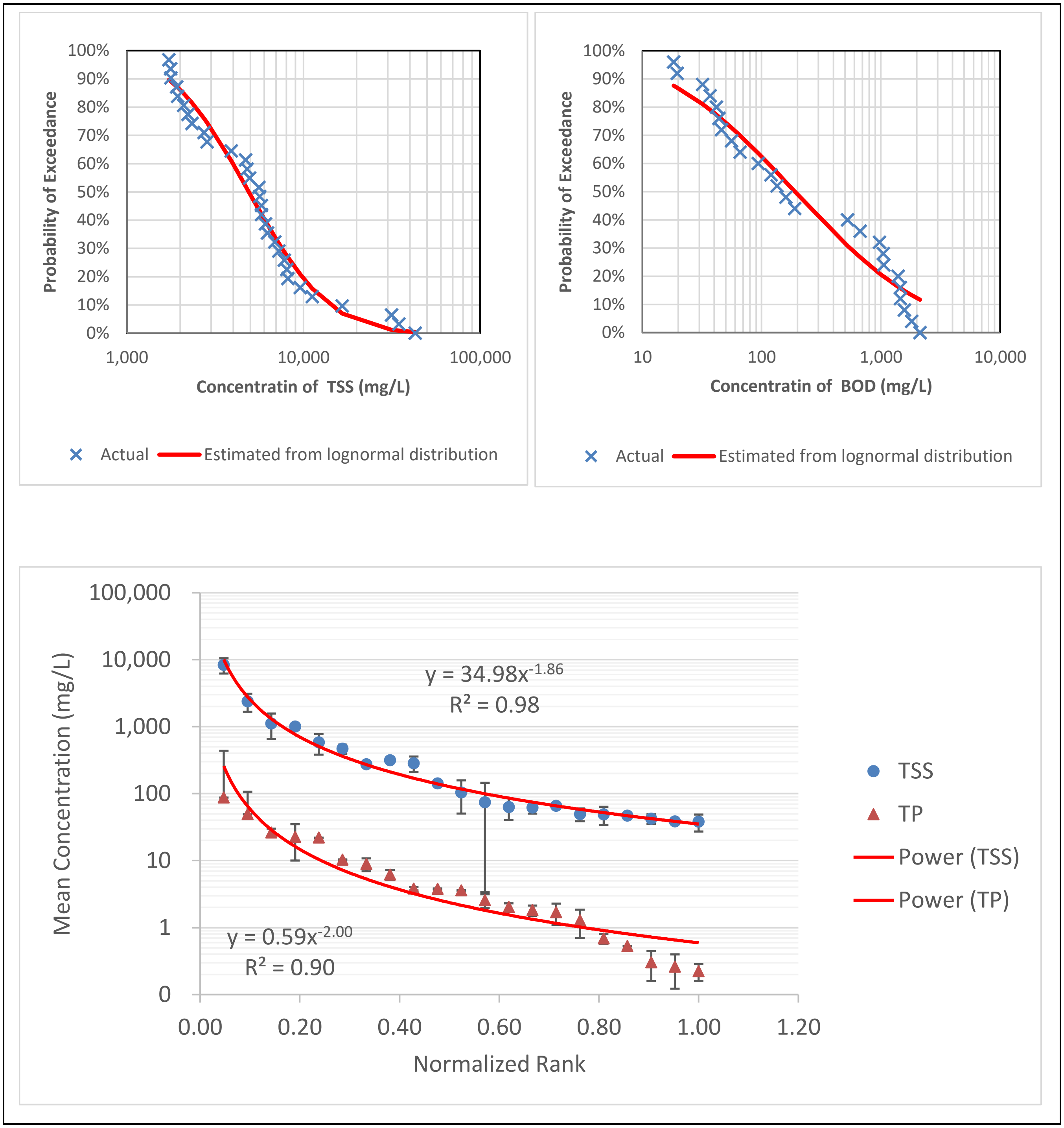

Figure 4-2: Probability of Exceedance, estimated vs. predicted using lognormal distribution for Potato wash-water (a) TSS and (b) BOD, and (c) Normalized Rank vs. Mean Concentration Curves and corresponding Power Functions for fitting data for TSS and TP.

The statistical parameters of the lognormal distribution, location (μ) and scale (σ) were calculated for the different water quality parameters for this study, using the developed power function relationships. The relationship between the mean (m), variance (ν), location (μ), scale (σ), and confidence interval (CI) for the lognormal distributions are presented in Eqs. (1) – (4) (Atieh et al. 2017). The confidence interval at 95% was calculated for each water quality parameters, giving an indication of the lower and upper limits expected. Eq. (4) is used to calculate the confidence interval, based on the modified Cox method, where n is the number of samples and z is the percentile of standard normal distribution (Zhou & Gao 1997). This is a naïve approach, which utilizes z as the multiplier. However, when t-distribution is used as the multiplier, it is referred to as the modified Cox method.

$$\mathrm{m} = \exp\left(\mu + \frac{\sigma^2}{2}\right) \tag{1}$$

$$\mu = \ln\left(\frac{\mathrm{m}}{\sqrt{1+\frac{\nu}{\mathrm{m}^2}}}\right) \tag{2}$$

$$\sigma = \sqrt{\ln\left(1+\frac{\nu}{\mathrm{m}^2}\right)} \tag{3}$$

$$CI = \exp\left(\left[\left(\mu + \frac{\sigma^2}{2}\right) \mp \left(z\sqrt{\left(\frac{\sigma^2}{n} + \frac{\sigma^4}{2(n-1)}\right)}\right)\right]\right) \tag{4}$$

The EasyFit software was also employed to calculate the mean and standard deviation values for each water quality parameter. The values for μ and σ were confirmed and optimized using the solver function in Excel software to minimize RMSE. The purpose of this exercise was to validate values calculated by EasyFit. Verification of location and scale values (μ and σ) ensured statistically correct distribution were applied in obtaining the mean and CI, which are the lower and upper limits of water quality parameters, such as for TSS. The mean and CI values are valuable in determining percent reduction required by treatment process to meet regulatory effluent compliance for TSS and other monitored water quality parameters.

4.2.3 Development of water quality prediction model (Power-Rank Models)

Developing models to predict water quality parameters of wash-water requires the use of power functions, which helps to correlate water quality and normalized rank of the products. The power function is represented as, $y = f(x) = a(x)^b$. Parameter a serves as a scaling factor (σ), moving the values of xb up or down, leads to increase or decrease, respectively. The parameter b, called the power, determines the function's rates of growth or decay, the location factor (μ). While parameter y is the predicted value, i.e., TSS and parameter x is the normalized rank, defined below. Figure 2(c), highlights the transformed data with corresponding power function parameters for the mean concentration of TSS and TP vs. Normalized Rank. The power function is used to recognize a power trend, which might be difficult to see, but a simple log transformation of data set can reveal a pattern that is unique to power functions.

Thus, water quality data was log transformed to the y-axis and utilized the power function. In addition, a ranking of average and standard deviation values (x-axis) from high to low was used to define the magnitude of each water quality parameter. This was done by first sorting the average values from high to low, where the highest average value was ranked as 1 and lowest was ranked as the last number. The rankings were further normalized, from 0 - 1, where zero was the highest magnitude, while one was the lowest magnitude. The formula for normalized rank is as follows, rank divided by n, where n is a number of products in a water quality parameter, i.e., TSS has 17 mean concentrations corresponding to products. The normalization of ranks was important since not all water quality parameters have the same number of products. Normalized ranks vs. mean concentration plots were derived for all water quality parameters, both from averages and standard deviations values.

Some water quality data were unavailable for each sample. For example, some samples had missing TSS values but collected TP or vice versa. There were also missing BOD, COD while TDS was available within the same sample. In order to complete the data set, missing ranks were added based on the corresponding similar water quality parameters, for example, TSS with TP. The assumption was later verified by confirming the exponent values, b, of TSS and TP, where non-significant different values meant the assumption was correct for analysis.

4.2.4 Model performance evaluation

Statistical and graphical methods were used to assess the performance and validity of the Power-Rank models developed for wash-water quality prediction of the location and scale terms. The coefficient of determination (R^2) was used to understand the amount of observed variance within the models, Eq. (7). The root mean square error (RMSE) and mean absolute percent error (MAPE) were used to understand model accuracy and precision, Eqs. (8) and (9). RMSE show differences between the observed and predicted values in the units of the variable of study. In Eqs. (7) through (9), variables, O, and P are the observed and model predicted values, respectively, and n is the number of observations. While a bar over the letter O or P, represent the average value, i.e., $\bar{O}$ is the average value of the observed series. The noted statistical measures were utilized to understand the unique properties of the model performance.

$$R^2 = \left[\frac{\sum_{i=1}^{n} (O_i - \overline{O})(P_i - \overline{P})}{\sqrt{\sum_{i=1}^{n} (O_i - \overline{O})^2} * \sqrt{\sum_{i=1}^{n} (P_i - \overline{P})^2}} \right]^2 \tag{7}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (O_i - P_i)^2}{n}} \tag{8}$$

$$MAPE = \frac{100}{n} \sum_{i=1}^{n} \left| \frac{(O_i - P_i)}{O_i} \right| \tag{9}$$

4.3 Results

The wash-water quality parameters follow a lognormal distribution, as verified with the sampled data. This concept is demonstrated using TSS and BOD from washing wash-waters. Figure 2(a) and (b) show suspended (TSS) and dissolved (BOD) constituents as a good fit for the lognormal distribution, as shown by the probability of exceedance curves. The RMSE for TSS and BOD, in Figure 2(a) and 2(b), are 5 and 6 %, respectively. These error values are very low, suggesting a very good fit. A total of twenty-one different produce wash-water types were investigated for the nine water quality parameters. Two different types of waste streams are produced, first washing, and second, consisting of both washing and processing (cutting and peeling) (Lehto et al. 2009; Mundi et al. 2017). Wash-water quality parameters and their corresponding mean and standard deviations are highlighted in Table 4-2 for wash-waters from washing operations, and similarly Table 4-4 for wash-waters from washing and processing operations. The missing data, noted by the asterisk in Table 4-2 and 4-4, were calculated using the Power-Rank models. These tables depict average and standard deviation values corresponding to sampled and collected data, which consists of various facilities, operations, and wash-water types.

Table 4-2: Average and Standard Deviation of water quality parameters of different washing type wash-waters

AVG and STD	TSS		TS		TDS		TP		TN		COD		BOD		EC		NH_4-N	
Product	**AVG**	**STD**	**AVG**	**STD**	**AVG**	**STD**	**AVG**	**STD**	**AVG**	**STD**	**AVG**	**STD**	**AVG**	**STD**	**AVG**	**STD**	**AVG**	**STD**
Apple	60	50	600	170	950	470	87.3	85.4	3.2	1.0	300	290	120	120	1,550	580	0.1	0.1
Boston Lettuce	140	20	560	20	420	10	3.8	0.1	3.9	0.3	140	80	90	30	500	50*	0.3	0.1
Broccoli	40*	20*	680*	70*	360*	50*	0.3	0.1*	2.0	0.4*	450*	110*	320	100*	370	40*	5.1	2.9*
Carrot	2,690	1,330	3,780	1,920	1,570	500	3.8	0.2	43.7	144.6*	1,440	350	320	100	2,150	440	1.2	1.0*
Ginseng	1,120	900	1,600	750	720	500	22.5	35.7	4.0	3.2	320	150	50	90	830	170	1.3	2.9
Ginseng Seed	270*	40*	2,000	470*	880*	290*	49.3	53.5	17.0	2.8	730*	200*	450	430	1,600	1,490	23.9	27.7
Green Onion	50*	20*	2,500	670*	470*	90*	0.5	0.2*	9.2*	0.9*	140*	50*	40	20*	720	30*	0.2*	0.2*
Melons	320	10	920	20	600	30	10.4	0.1	24.0	0.8	300	20	80	20	670	20	0.4	0.1
Mixed[1]	470	170	1,030	130	650	240	8.9	7.2	22.6	0.8	150	33	50	60	800	30	0.2	0.2
Mushroom	280	240	1,230	890	900	800	2.0	1.8	18.5	23.9	2,880	2,410	130	140	1,850	1,700	11.8	15.9
Peppers	40	20	750	150	710	170	0.3	0.2	17.6	12.8	140	80	40	20	940	190	0.2	0.1*
Potato	8,370	9,970	5,340	2,680	1,060	520	26.2	28.9	39.7	36.7	4,340	4,110	610	690	1,510	750	39.8	40.6
Pumpkin/Gourd	50	50	1,130*	220*	3,760*	4,560*	22.0	14.1	8.1*	0.8*	390	120	10	10*	3,560	990	0.1*	0.1*
Snap Beans	50	20	680	90	630	100	0.7	0.1	7.8	0.4	160	40	50	40	810	240	0.3	0.2
Sour Cherry	70*	30*	1,230	320	340*	50*	1.3	0.9	7.0	1.3*	2,720*	1,920*	1,030	600	350	70	1.1	0.6*
Spinach	100	100	540	90	440	50	2.6	1.8	3.0	0.4	310	270	330	250	420	50*	0.6	0.2
Squash/Sweet Potato	580	250	680	120	100	130	1.8	0.5	6.2	0.7	200	80*	42	20	330	80	1.0	0.5
Sweet corn	70	80*	490	50*	420	50*	3.6	0.4*	3.9*	0.6*	220	220	160	80*	640	60*	0.4*	0.1*
Sweet Potato	1,000	860	5,610	7,170	490	430	6.2	4.6	6.4	5.1	10*	40*	10	20	320	160	0.1	0.2
Tomato	60	60	1,590	1,110	1,720	1,130	1.7	2.7	1.7	0.8	90	60	20	10	1,470	1,030	0.2	0.1
Zucchini	40	10	570	20	530	10	0.2	0.02	17.4	0.5	50	20	10	10	780	10	0.2	0.1*

*Estimated using Power-Rank Models
[1]Mixture of carrot, spinach, and beetroot

Table 4-3: Normalized ranks of water quality parameters of different washing type wash-waters (washing only)

Normalized Rank (0.05-1)	TSS		TS		TDS		TP		TN		COD		BOD		EC		NH_4-N	
Product	**AVG**	**STD**	**AVG**	**STD**	**AVG**	**STD**	**AVG**	**STD**	**AVG**	**STD**	**AVG**	**STD**	**AVG**	**STD**	**AVG**	**STD**	**AVG**	**STD**
Apple	0.67	0.62	0.81	0.52	0.24	0.24	0.05	0.05	0.81	0.38	0.52	0.24	0.43	0.38	0.24	0.29	0.95	0.71
Boston Lettuce	0.48	0.86	0.90	0.86	0.81	0.81	0.48	0.95	0.76	1.00	0.81	0.67	0.48	0.62	0.76	0.76*	0.62	0.86
Broccoli	0.95*	0.90*	0.76*	0.76*	0.86*	0.86*	0.95	0.86*	0.95	0.86*	0.33	0.48	0.24	0.29*	0.86	0.86*	0.19	0.19*
Carrot	0.10	0.10	0.14	0.14	0.14	0.14	0.43	0.71	0.05	0.05*	0.19	0.19	0.29	0.43	0.10	0.33	0.29	0.29*
Ginseng	0.14	0.14	0.29	0.38	0.38	0.38	0.19	0.14	0.71	0.29	0.38	0.43	0.67	0.48	0.43	0.48	0.24	0.24
Ginseng Seed	0.33*	0.57*	0.24	0.29*	0.29*	0.29*	0.10	0.10	0.48	0.33	0.24	0.33	0.14	0.14	0.19	0.10	0.10	0.10
Green Onion	0.86*	0.81*	0.19	0.24*	0.62*	0.62*	0.86	0.76	0.38*	0.57*	0.76	0.76	0.76	0.76*	0.62	0.95*	0.71*	0.57*
Melons	0.38	0.95	0.57	0.95	0.57	0.57	0.29	0.90	0.14	0.52	0.48	1.00	0.52	0.67	0.67	0.90	0.48	0.81
Mixed[1]	0.29	0.33	0.48	0.62	0.48	0.48	0.33	0.29	0.19	0.43	0.71	0.90	0.57	0.52	0.52	0.67	0.76	0.48
Mushroom	0.43	0.29	0.43	0.33	0.33	0.33	0.62	0.48	0.24	0.14	0.14	0.14	0.38	0.24	0.14	0.05	0.14	0.14
Peppers	1.00	0.71	0.62	0.57	0.43	0.43	0.90	0.67	0.29	0.19	0.86	0.62	0.81	0.81	0.38	0.43	0.81	0.90
Potato	0.05	0.05	0.10	0.10	0.19	0.19	0.14	0.19	0.10	0.10	0.05	0.05	0.10	0.05	0.29	0.24	0.05	0.05
Pumpkin/Gourd	0.81	0.52	0.43*	0.43*	0.05*	0.05*	0.24	0.24	0.43*	0.62*	0.29	0.52	1.00	1.00	0.05	0.19	1.00	1.00
Snap Beans	0.76	0.76	0.67	0.71	0.52	0.52	0.81	0.81	0.52	0.90	0.67	0.81	0.62	0.57	0.48	0.38	0.57	0.62
Sour Cherry	0.71*	0.67*	0.38	0.48	0.90*	0.90*	0.76	0.52	0.57	0.48*	0.10	0.10	0.05	0.10	0.90	0.62	0.33	0.33*
Spinach	0.52	0.38	0.95	0.81	0.76	0.76	0.57	0.43	0.90	0.95	0.43	0.29	0.19	0.19	0.81	0.81*	0.43	0.52
Squash/Sweet Potato	0.24	0.24	0.71	0.67	1.00	1.00	0.67	0.57	0.67	0.76	0.62	0.57	0.71	0.71	0.95	0.57*	0.38	0.38
Sweet corn	0.57	0.43*	1.00	0.90*	0.95	0.95*	0.52	0.62	0.86*	0.71*	0.57	0.38	0.33	0.33*	0.71	0.71*	0.52*	0.76*
Sweet Potato	0.19	0.19	0.05	0.05	0.71	0.71	0.38	0.33	0.62	0.24	0.95	0.86	0.90	0.86	1.00	0.52	0.90	0.43
Tomato	0.62	0.48	0.33	0.19	0.10	0.10	0.71	0.38	1.00	0.67	0.90	0.71	0.86	0.90	0.33	0.14	0.67	0.67
Zucchini	0.90	1.00	0.86	1.00	0.67	0.67	1.00	1.00	0.33	0.81	1.00	0.95	0.95	0.95	0.57	1.00	0.86	0.95*

*Estimated using Power-Rank Models
[1]Mixture of carrot, spinach, and beetroot

Table 4-4: Average, Standard Deviations and Normalized ranks of different washing and processing type wash-waters (washing and processing)

AVG and STD																		
	TSS		TS		TDS		TP		TN		COD		BOD		EC		NH_4-N	
Product	AVG	STD	AVG	STD	AVG	STD	AVG	STD	AVG	STD	AVG	STD	AVG	STD	AVG	STD	AVG	STD
Apple	80	54	2,760	2,370	5,190	5,020	9.3	13.6	10.1	14.5	1,160	1,670	690	990	1,150	860	1.0	0.74
Carrot	1,450	1,110	6,470	2,560	4,340	1,670	2.2	1.5	2.6	0.30	2,340	3,000	750	1150	670	190	0.6	1.8
Mixed[2]	530	130	1,630	440	1,100	330	4.0*	3.5*	45.0	1.00*	14,700*	5,570*	1,830	5,200 *	620*	80*	5.6	2.8*
Potato	5,220	3,930	6,220	4,130	1,000	720	33.3	17.0	27.0	23.1	4,070	2,560	570	280	1,520*	1,670*	7.2	8.5
Normalized Rank (0.05-1)																		
	TSS		TS		TDS		TP		TN		COD		BOD		EC		NH4-N	
Product	AVG	STD	AVG	STD	AVG	STD	AVG	STD	AVG	STD	AVG	STD	AVG	STD	AVG	STD	AVG	STD
Apple	1.00	1.00	0.75	0.75	0.25	0.25	0.50	0.50	0.75	0.50	1.00	1.00	0.75	0.50	0.50	0.50	0.75	1.00
Carrot	0.50	0.50	0.25	0.50	0.50	0.50	1.00	1.00	1.00	0.75	0.75	0.50	0.50	0.75	0.75	0.75	1.00	0.75
Mixed[2]	0.75	0.75	1.00	1.00	0.75	1.00	0.75*	0.75*	0.25	1.00	0.25*	0.25*	0.25	0.25*	1.00	1.00*	0.50	0.50*
Potato	0.25	0.25	0.50	0.25	1.00	0.75	0.25	0.25	0.50	0.25	0.50	0.75	1.00	1.00	0.25	0.25*	0.25	0.25

*Estimated using Power-Rank Models
[2]Mixture of iceberg lettuce, broccoli, carrots, green peppers, celery, and apple

The different fruit and vegetable types can be categorized into: root-vegetable (carrot, ginseng, ginseng seed, green onion, potato, and sweet potato), tree fruit (apple and sour cherry), leafy greens (Boston lettuce and spinach), mixed (carrot, spinach, and beetroot) and above ground (broccoli, melons, mushroom, peppers, snap beans, pumpkin, sweet corn, tomato, and zucchini). It was evident that many root vegetables show high levels of solids as indicated by the TSS and TS values in both types of waste streams. These results suggest the need for physical treatment (settling pond) to reduce solids loading.

Conversely, tree fruit and above ground commodities show a low level of TSS and TS, which might be easier to treat for suspended solids. However, this was not the case for TP, TN, COD, and BOD, suggesting the requirement for a biological and/or chemical treatment to handle the high loads of contamination. For example, one of the tree fruit wash-water samples had very high TN and TP due to the use of dunk tank for washing, with a 5-day water change cycle. Some facilities utilize dunk tanks which serve as batch processes to clean the commodity. Unfortunately, these dunk tanks can accumulate contaminants, such as solids, TN, TP, BOD and pathogens. In addition, considerable differences exist in flows/volumes for small-scale seasonal operations as compared to large operations, which use continuous water flow for washing and processing, diluting the contaminants. TP was approximately 10 mg/L for most products except for root vegetables. In general, TN values were much higher in comparison to TP. Higher BOD, COD and EC values were noticed for root vegetables in comparison to others. Highlighting that physical treatment (settling pond) alone will not suffice for root-vegetables, the addition of aeration, biological, and/or chemical treatment will be required. Different types of produce, based on their ranks, which can be similar for a category of wash-water (i.e., root vegetable) can highlight contaminants of concern to target for treatment. These trends and results are in line with previous studies by Mundi et al. (2017, 2015), Kern et al. (2006), Lehto et al. (2009, 2014), Casani et al. (2005).

Estimated values for average and standard deviation serve as a valid range to assess regulatory compliance or determining the degree of treatment/technology required. However, some of the predicted values seem to be over or understated. This is due to the estimation of normalized ranks which introduce small errors into the system and impact the prediction accuracy of the Power-Rank models. Figure 2(c) shows higher ranks for the TP model (curve) overestimating the TP values. Similarly, washing and processing operation wash-waters were summarized in Table 4-4. It can be seen that much higher levels of solids and oxygen demand, as noted by TS, COD, and BOD. This is to be expected as Table 4-4 represents operations which part-take in cutting, budding, and peeling stages, increasing the organic fraction of wash-waters (Kern et al. 2002; Lehto et al. 2017).

The normalized ranks for the Power-Rank model are derived in Table 4-3 for washing operations, and Table 4-4, bottom, for washing and processing operations. While most are based on sampled values, some are estimated, as indicated by the asterisk marks. The normalized ranks in Table 4-3 and 4-4 may represent a source of error, as these were estimated based on the concept that similar wastewater constituents have similar levels of contamination. Small inaccuracies are inherent to estimating normalized rank, which can be magnified when using the Power-Rank models to predict water quality parameters. In addition, it is important to note that if the estimated normalized rank value lies at either end of the predicted curve of the Power-Rank models, then it will have a larger error associated with it due to the fitting of the curve.

Table 4-5: Power-Rank Model Parameters and Performance Parameters

	TSS		TS		TDS		TP		TN		COD		BOD		EC		NH_4-N	
Washing Type Wash-water																		
	AVG	**STD**	**AVG**	**STD**	**AVG**	**STD**	**AVG**	**STD**	**AVG**	**STD**	**AVG**	**STD**	**AVG**	**STD**	**AVG**	**STD**	**AVG**	**STD**
a	34.99	9.83	527.80	43.52	315.47	41.48	0.59	0.09	3.29	0.30	91.50	28.90	17.26	12.00	0.42	0.03	0.11	0.03
b	-1.87	-2.33	-0.90	-1.91	-0.81	-1.54	-2.00	-2.90	-1.07	-2.03	-1.44	-1.79	-1.69	-1.66	-0.79	-1.75	-2.12	-2.68
R^2 (%)	98	97	97	88	73	49	90	90	85	95	93	94	80	86	90	80	97	96
RMSE (units)	470	487	631	1619	125	207	38	114	10	2	740	638	431	267	0.3	1	6	17
MAPE (%)	15	25	9	42	20	84	56	85	27	21	19	22	78	41	17	55	39	25
Washing and Processing Type Wash-water																		
a	146.36	63.42	2,044	831.59	1,023.5	379.64	2.26	2.09	4.27	0.37	1,244.8	1,789.8	522.98	364.46	0.62	0.08	0.72	0.88
b	-2.78	-3.18	-0.99	-1.33	-1.32	-1.93	-1.96	-1.75	-1.93	-3.34	-1.70	-0.82	-0.83	-1.92	-0.65	-2.19	-1.89	-1.67
R^2 (%)	92	95	79	67	82	98	99	81	85	74	97	88	92	75	91	91	84	95
RMSE (units)	888	702	1353	856	1086	271	1	5	10	11	175	180	130	216	0.2	0.25	2	0.3
MAPE (%)	45	31	22	45	25	12	3	32	42	46	6	6	11	21	7	20	34	11

Power-Rank model parameters, a and b, in addition to performance indicators, such as R2, RMSE, and MAPE are highlighted in Table 4-5. Parameter a and b are reported to 2 decimal places to allow the model to predict to a greater accuracy, while the performance indicators are reported to zero decimal place for ease of interpretation. The scalar parameter, b, for the Power-Rank models are comparable and show hidden trends. Upon close inspection of Table 4-5, one can see that TSS, TP, and NH_4-N all have values around 2. Similarly, BOD and COD have values around 1.6, and TS, TDS, TN and EC have values of about 0.8. These highlight parameters with similar Power-Rank model curves, or in simple words they are correlated. These correlations, however, were quite different for washing and processing wash-waters. The parameter b values for TSS was standalone around 3, TDS, TN and NH_4-N have values around 1.6, while TS, TP, COD, BOD and EC all have values around 1. These are useful in reducing the Power-Rank models further, making them more robust and convenient. The rank along with the characteristics of the power function (a and b) will determine the level of wash-water quality, which then can be used for assessing the level of treatments required (physical, biological, and/or chemical).

The Power-Rank model equations show a very good fit for the majority of the water quality parameters as indicated by R2. RMSE values highlight the standard errors in terms of units, which are useful when applying models for practical applications. Given the variability of water quality parameters within wash-waters, variability is also expected in the RMSE. In addition, water quality parameters with a large number of data points show lower RMSE, while few samples lead to higher RMSE. However, the overall trend showed that the waters derived from different facilities processing the same product type show similar characteristics for some water quality parameters, as indicated by RMSE. This highlights that there was little variation with respect to wastewater composition derived from different facilities processing the same product type. This may be because similar products are processed in a similar manner. More importantly, a distinction was made in this study between washing versus washing and processing waste streams. This implication allows the extension of the research to be applied to other geographical locations around the world utilizing similar processes and unit operations. MAPE also highlights the error in terms of percentage, which also varies in range. Error and performance parameters do not show concerning trends or extreme values, validating the Power-Rank models for use in determining the different levels of treatment needed for implementation, and to meet effluent requirements post-treatment.

Previous studies from Kern et al. (2006), Lehto et al. (2009, 2014), Casani et al. (2005) highlighted characteristics and did not show such a wide and diverse set of data, as given by this study with the Power-Rank models. The use of the Power-Rank model can be demonstrated as follows. Say TSS from a ginseng washing the only operation is to be predicted. The average TSS value can be determined using the Power-Rank coefficients from Table 4-5, which is equal to Axb or 34.99*x-1.87 where x is the normalized rank. The value of x can be obtained from Table 4-3 (washing only), which is equal to 0.14. Therefore, average TSS value is equal to 34.99*(0.14)-1.87, or 1,383 mg/L. Likewise, the Power-Rank model for standard deviation is calculated as follows, 9.83*(0.14)-2.33, were coincidently the rank for standard deviation is also 0.14 (Table 4-3). Hence the standard deviation is equal to 960 mg/L. As a result, the TSS value for a wash-water from a ginseng washing operation from the developed models is 1,380 ± 960 mg/L (Average ± Standard Deviation). These levels can be used in determining effluent values for different treatment processes while evaluating various wash-water treatment options, including capacity using the flows generated by the system in question.

The equations listed in Table 4-5 were derived from a large number of facilities with varying operating and management conditions and can be used to predict water quality parameters for an average set of conditions. Prior to this study, the ranges and values of wash-water quality were unknown, making it difficult to identify potential treatment options. However, it should be noted that the current models do not account for the type of soil attached to the produce. Wash-water that contains mineral soils versus organic soils will exhibit different characteristics. For example, wash-water with mineral soils might be better suited for settling technologies, while wash-water contaminated by organic based soils are best suited for a technology like dissolved air flotation (Mundi & Zytner 2015). Similar challenges could exist for a parameter like nutrients. Additional wash-water data is needed to determine the impact the various parameters have on the Power-Rank models and is being considered for future studies.

Having the Power-Rank models shown in this paper provides researchers, technology providers and government officials the information needed to better understand the potential magnitude of the impact untreated wash-waters can have on the environment. The wash-water water quality parameters can be utilized for watershed studies to estimate the impact on sensitive water bodies, such as lakes and streams from agricultural operations involved in washing and processing fruits and vegetables. They also can provide insight on whether the wash-water will meet sewer discharge limits if the producer is serviced with a municipal sewer. In addition, the models will provide the information needed to design and evaluate wastewater treatment processes to achieve treatment objectives that may be set by producers or government agencies. The predicted raw wash-water quality parameters coupled with operating parameters, such as flow, allow consultants to determine the required amount of settling area needed for solids, or the amount of aeration/aerators required for biological breakdown of organic matter.

Wastewater discharge requirements are listed in Table 4-5 for various Canadian jurisdictions in comparison to German limits (specific to fruit and vegetable industry wastewaters). Using the predicted effluent quality from untreated wash-water via the Power-Rank models shows how much treatment is required prior to release. The target water quality is indicated by the Provincial Water Quality Objectives (PWQO) (see Table 4-6), which allows the release to surface water. The water quality parameters to meet and their corresponding limits are listed as 25 mg/L for TSS, 0.02 mg/L for TP, and 0.02 mg/L for NH_4-N (MOECC 2016).

Table 4-6: Effluent requirements for wastewater discharge in Canada and Germany, water quality parameters measured in mg/L

	Target concentration for drinking water[1]	Target concentration for sanitary and combined sewer discharge[2]	Provincial Water Quality Objectives[3]	German Regulation Limits for Fruit and Vegetable Wastewater[4]
TSS	-	350	25[a]	-
TS	-	-	-	-
TDS	500	-	-	-
TP	0.01	10	0.02	2
TN	-	-	-	18
NH_4-N	0.02*	-	-	10
BOD	-	300	20[a]	25
COD	-	-	-	110

[1]Data obtained from Supporting Document for Ontario Drinking Water Quality Standards, Objectives and Guidelines, Tables 1, 2, and 4
[2]Data obtained from City of Toronto Sewer Discharge and Storm Water Discharge Limits, Table 1
[3]Data obtained from Provincial Water Quality Objectives for Surface Water, some parameters are subjected to additional conditions
[4]Federal Law Gazzete, The Ordinance on Requirements for the Discharge of Waste Water into Waters
[a]Limits for effluent discharged to receiving waters; Guidelines for Effluent Quality and Wastewater Treatment at Federal Establishments
*Additional requirements related to pH

The current state of guidelines highlights three different type of legally enforceable requirements, which are based on either achievable treatment technology, the 75th percentile effluent water quality to meet the set PWQO, and/or site-specific receiving water quality requirements based on the assimilative capacity of the receiving watercourse (Trenouth et al. 2018). Emerging and new affordable technologies can make it easier to meet achievable/desired treatment requirements, while implementation/enforcement of the receiving water quality requirements can be very expensive/impractical. Thus, it is suggested that the 75th percentile confidence interval (calculated easily using the models presented in this study) be adopted as the effluent limit for fruit and vegetable wash-water, treated or untreated.

4.4 Conclusion

The study employs novel regression techniques for comprehensive fruit and vegetable washing and processing wash-waters for many different commodities in Southern Ontario to develop functional tools for the prediction of wash-water quality. A total of 239 samples were selected based on availability and collected data for a representation of fruit and vegetable washing and processing industry. Key water quality parameters include TSS, TDS, TS, TN, TP, EC, NH_4-N, COD and BOD, which follow a lognormal distribution. This study demonstrates how Power-Rank models derived using regression analysis can be used to predict the wash-water quality for fruit and vegetable processing wash-water. The models derived from the two different types of operations encountered, washing versus washing and processing, performed very well as indicated by R^2 values. The RMSE and MAPE performance parameters indicate the expected error boundaries, which is in the range of acceptable. The datasets were an amalgamation of the industry-wide samples. Variability is inherent to the developed models and may be improved by increasing sample size for various product types. Specifically, for a low number of samples, such as broccoli, sweet corn, green onions, which only have one sample.

The models developed in this study complement previous characterization studies which show the range of water quality expected from different wash-waters. The advantages of this study are that it includes additional data and Power-Rank models for water quality parameters predictions. Some limitation exists, such as over and underestimating the mean and standard deviation of products for which the rank values were estimated. The high variability of water quality parameters seen in wash-waters means high levels of treatment may be required to treat and dispose wash-water into the environment (surface, lakes, and rivers). Therefore, the prediction of water quality levels based on product, and the corresponding rank can yield very good estimates of expected water quality from washing and processing facilities. This information is valuable for farmers, government agencies, consulting firms, technology providers, and other stakeholders interested in determining wash-water rudimentary treatment and sizing from predicted levels of water quality parameters. The study was successful in capturing a wide variety of information and concatenating into a useful tool for making an important decision on the treatment of wash-waters.

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Chapter 5: Multiple Linear Regression and Artificial Neural Network Models for Predicting Water Quality of Treated Fruit and Vegetable Wastewater

Chapter 5 extends the work done on treatment feasibility in Chapter 3 that produced treatment selection matrices. Combined with the additional treatment data from OMAFRA datasets, the tables were converted to equations/models with the use of multiple linear regression and artificial neural network modelling methods. These can be used to predict the level of treatment achievable under one of the tested treatments in this study.

The work has been prepared and will be submitted to a peer-reviewed journal may be cited as follows:

- *Mundi, G. S., Zytner, R. G., Warriner, K., & Gharabaghi, B. (In preparation). Multiple Linear Regression and Artificial Neural Network Models for Predicting Water Quality of Treated Fruit and Vegetable Wastewater. Submission planned for Water Science and Technology journal.*

5.1 Introduction

The need for fresh water is essential in food processing, as it is used in many different stages of processing, including washing, cutting, peeling, sanitizing, cooling, transporting, and for equipment and machinery cleaning (Lehto et al. 2014). Different quality waters are used in different stages, however, the highest quality waters, that of the potable standard is required to be used for final cleaning/rinsing. Chlorinated waters or other forms of sanitizers are often used to provide potable water standard for final rinsing to ensure microbiological control and food safety. Due to the heavy use of water, large quantities of wastewater are generated in the fruit and vegetable washing and processing industry, including the fresh-cut industry (Gil et al. 2009). In many cases, the wastewater (used once and wasted) or wash-water (recirculated waters reused for washing) are often rich in solids, BOD, and other contaminants (Kern et al. 2006). Wastewater and wash-waters require adequate treatment and disinfection before they are either reused in the process or disposed of. Treatment of waters is necessary to provide suitable food safety when water is reused within the process (solids, salts, and pathogens), and to protect the environment from receiving excess loads of contamination (nutrients).

Sensitive parts of the environment, such as lakes are at a risk of eutrophication (algae blooms), which will impact the ecosystem supported by the lake, including recreational use by humans. The Province of Ontario, Canada is highly dedicated to protecting lakes contained inside the province, such as Lake Simcoe, and lakes bordering the province, such as Lake Ontario, Erie, and Huron (Lake Simcoe Region Conservation Authority 2009). In addition to lakes, groundwater quality may also be jeopardized by excessive nutrient and solids loading. Also, disposal of wash-water via irrigation on farm fields may cause blockage of porous soils, through buildup from dissolved and suspended constituents like calcium, sodium, magnesium (sodium adsorption ratio) and solids (Halliwell et al. 2001). The influence of climate change and extreme weather events on water quantity and quality also need to be considered. Thus, water reclamation and reuse is often practiced to reduce water utilized in many water-intensive industries like the fruit and vegetable washing and processing sector.

Current water reuse within Ontario's fruit and vegetable industry highlights the use of advanced treatment/reuse systems (MBR) or partial treatment using physiochemical and biological treatments. Freshwater supplementation (i.e., 50% treated waters and 50% fresh water) to meet drinking water regulations for process need is also practiced (Mundi et al. 2017). Some root vegetable washing facilities practice direct reuse of the wash-waters for preliminary soil removal/washing, often after settling treatment to reduce the solids loading in recycled water. Specific regulations governing water quality for process needs within the fresh fruit and vegetable industry state the requirements of potable water for final rinsing and the use of non-potable grade water for soil washing which is acceptable (Minister of Justice 2012). Additional municipal, provincial, and federal regulations on water and food safety may also apply.

Wastewater in this industry is commonly referred to as wash-water, the characteristics of which are dependent on the type of commodity/crop and operation. Thus, the treatment selection process can become a daunting task requiring technical professionals, which can be costly for end users, such as farmers, producers, and processors. Tools that address treatment, water reuse feasibility, and its prediction are lacking. Thus, the objective of this study is to address the knowledge gap within the industry by developing models (set of tools) to predict treatment effectiveness through reduction efficiencies. The models are developed using well known multiple linear regression (MLR) techniques, and the more recent and popular method of artificial neural network (ANN) methods. The models will predict water quality parameters, such as total suspended solids ($TSS_{Treated}$), chemical oxygen demand ($COD_{Treated}$), biological oxygen demand ($BOD_{Treated}$), total nitrogen ($TN_{Treated}$), total phosphorus ($TP_{Treated}$), and Ammonia as Nitrogen (NH_4-$N_{Treated}$), of the treated waters dependent on operation type, and wastewater treatment process.

This study is part of a larger study on investigating, identifying and providing useful information and practical tools for understanding treatment of wash-waters. The study compiled by Mundi et al. (2017) highlighted wash-water characterization analysis and table based decision tools to showcase treatment effectiveness. Continuing from the previous study, the goal now is to convert the rating system utilized in Mundi et al. (2017) to numerical tools, using MLR and ANN techniques. Additional data is also added from other sources, highlighted in Mundi et al. (2018) containing data from Ontario Ministry of Agriculture Food and Rural Affairs (OMAFRA) to test and validate the models. Completion of the models will allow estimation of water quality from bench scale treatments such as settling, settling with coagulation and flocculation, screening, hydro-cyclone, centrifugation, dissolved air flotation, and electrocoagulation, and full-scale treatments ranging from settling ponds to membrane bioreactor system. These predicted water quality parameters can be utilized to address treatment options and to assess how they meet the regulatory compliance for wastewater disposal and reuse. Doing so would be very useful for farmers, producers, processors, technology providers, consultants, and regulators.

5.2 Literature Review

Studies in the literature have demonstrated the use of MLR and ANN models as a vital tool in predicting water quality of wastewater from different sectors. Such as in urban areas to predict municipal wastewater COD and BOD (Obaid et al., 2015), industrial application to predict TSS, BOD, COD, and others from optical monitoring of wastewater (Tomperi et al. 2017), for construction applications to predict soil loss (Trenouth & Gharabaghi 2015), in the water resource field to predict stream sediment load and concentration (Atieh et al. 2015), for wetlands to predict TP removal rates (Li et al., 2015), in sewage treatment plant to predict BOD (Khambete & Christian 2014), in assessing electrocoagulation treatment by predicting hardness, COD, and turbidity (Zhao et al. 2014), and predicting water main failure (Asnaashari et al. 2013).

Many of these studies also utilized the modern powerful ANN models to compare and validate the finding of MLR and to improve predictive models by increasing accuracy through ANN techniques. The quality of wastewater generated in any process industry is generally indicated by its water quality parameters, such as BOD, COD, TS, SS, TN, TP, TDS, and others. Utilization of raw water quality parameters in combination to process parameters and treated water quality parameters have led to many useful models for prediction through MLR and ANN techniques. These tools are employed to make prediction of expensive or hard to test water quality contaminants, (BOD, TN, and TP), appropriate treatment decisions, and to decide the fate of the treated waters, reuse (drinking, agricultural, and process) or dispose (return to rivers, lakes, and seas).

The ANN models are more powerful in comparison to MLR models as they are able to find complex patterns in datasets which are not easily described by a set of MLR equations. ANN utilize advanced nonlinear functions in comparison to MLR techniques which are linear. However, ANN models require a much larger dataset in comparison to MLR. Prediction of BOD and COD from TSS, TS, pH, and temperature using MLR and ANN methods were highlighted by Abyaneh (2014) and Verma and Singh (2013) have demonstrated ANN as superior to MLR in some cases. More specific application in the field of fruit and vegetable science include prediction of kiwifruit firmness (Torkashvand et al. 2017), treatment of potato wash-water (Bosak et al. 2017), and predicting chlorine demand of fresh and fresh-cut produce based on produce the properties of wash water (Chen & Hung 2016). Review of the literature has shown than MLR and ANN models have been used to develop convenient tools for estimating water quality, which is dependent on different treatment technology tested.

5.3 Materials and Methods

5.3.1 Study area, wash-water samples, and laboratory analysis

The study was carried out in Southern Ontario, Canada. The selected wastewaters and wash-waters were collected from various fruit and vegetable washing and processing facilities, including fresh-cut produce. Many of the facilities were on farm operations, which currently utilize passive treatments such as settling ponds, while other samples were collected from urban facilities, which dispose wastewaters to the municipal sewer. Wash-waters were generated in many applications where fruits and vegetables were washed to remove soil, processed, and/or provide microbiological decontamination. Different processing steps were required based on the type of vegetable or fruit being processed.

Root vegetables such carrots, potatoes, and ginseng required washing to clean and remove soils that are attached to root material. This process is stated as washing (W), however whenever the root vegetable or another fruit or vegetable requires processing, such as cutting/peeling, then the process is stated as washing and processing (WP). In addition, the products were also classified as a root vegetable, tree fruit, leafy green, and above ground. The full dataset consists of four independent subsets, two of which were studied and presented in Mundi et al. (2017). The remaining two datasets were introduced for characterization in Mundi et al. (2018) and were provided by Ontario Ministry of Agriculture Finance and Rural Affairs (OMAFRA). The results presented in Mundi et al. (2017) were table based, or decision matrices, where the user would read the proper treatment combination of the charts. These decision matrices will now be converted to models (MLR or ANN). Additional data from OMAFRA in combination to Mundi et al. (2018), were used to develop Power-Rank models for characterizing water quality and to fill data gaps to develop MLR and ANN models as presented herein. The methodology is illustrated in Figure 5-1.

A total of 245 samples were contained in the master dataset, 223 contained data on bench scale treatments, while the other 22 related to full scale treatments. The bench scale treatments consisted of screening (S), hydrocyclone (HC), settling using Jar Test method with optimized coagulation and flocculation process (C&F), dissolved air flotation using optimized coagulant dosage (DAF), centrifuge (C), and electrocoagulation (EC&F). Full-scale treatments sampled included a single tank settling (SET1), settling followed by open grass (SET1G), three settling tanks in series (SET3), pond (POND), sequential batch reactor with four stages – settling, aeration, nutrient removal, settling (SETBIO4), and membrane bioreactor with reverse osmosis and UV disinfection

(MBR+RO+UV). The samples were collected at random from each facility under normal operating conditions. The samples collected consisted of (1) raw wash-water, the wastewater that is produced by the washing and/or processing operations, (2) post-onsite treatment, the effluent treated wastewater employed by the facility. The raw wash-water and the post-onsite treatment samples were analyzed for a suite of water quality tests.

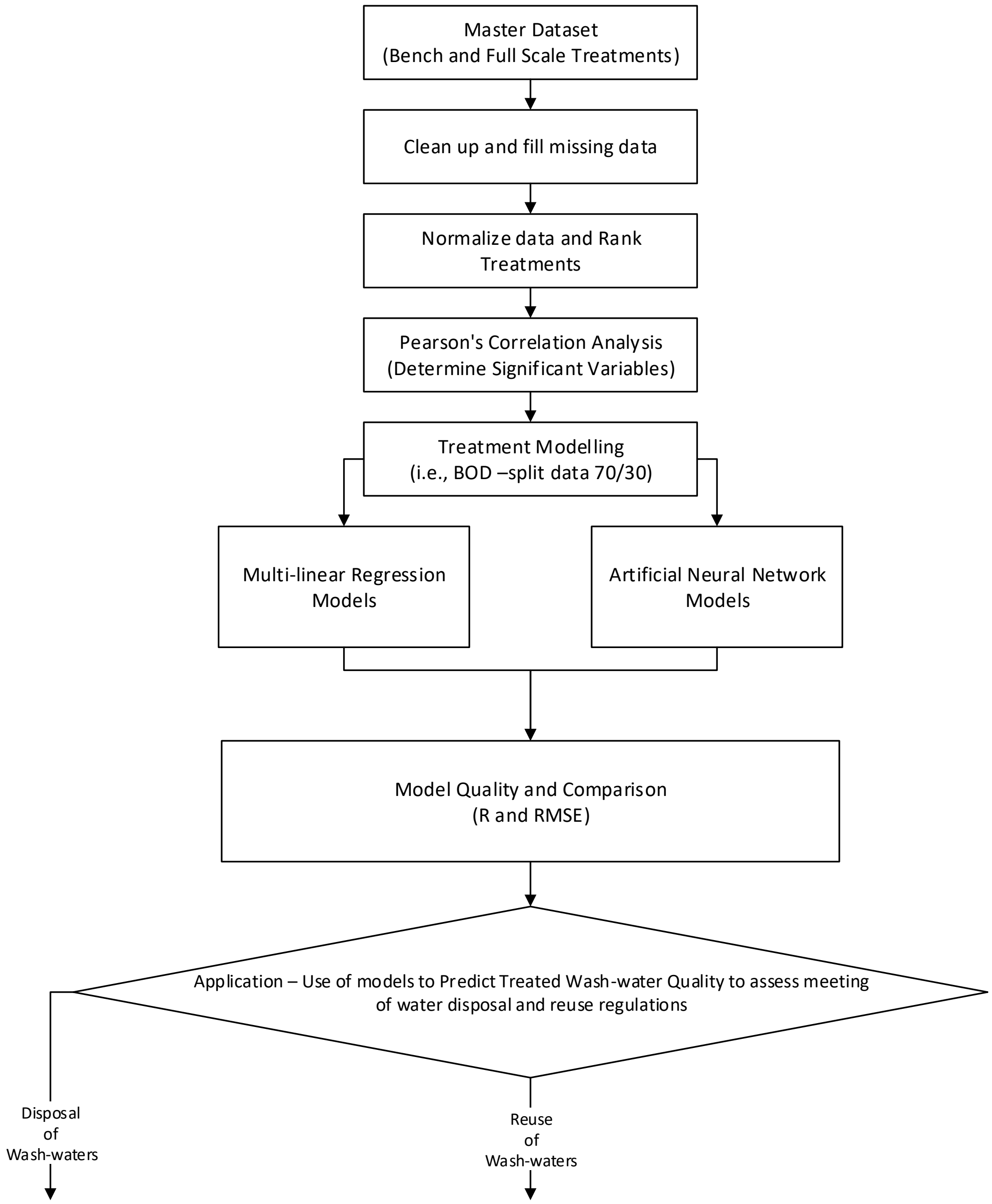

Figure 5-1: Process flow diagram of for developing MLR and ANN models and their applications

In addition, the raw wash-waters were also treated with six bench scale treatments. These include the following treatments; settling (jar test control - 1 minute rapid mix at 100 rpm, 10 min slow mix at 30 rpm, and 20 min settling), settling with coagulation and flocculation process (jar test with coagulants varying in dosage from 5 to 400 mg/L, 1 minute rapid mix at 100 rpm, 10 min slow mix at 30 rpm, and 20 min settling) , screening (sieve 100 um), centrifugation (1801 x G for 3-minute), dissolved air flotation (10-minute retention of recycle water at rate of 50 % and 10-minute detention for flotation) using optimized coagulant dosage as determined earlier using jar test, hydro-cyclone (4 mm apex, 6.7 mm vortex finder, 48 mm diameter, and 1.3 L/min of flow), and electrocoagulation (Maximum of 575.1 cm^2 surface area, minimum reaction time of 10-minutes, and maximum of 0.27 kWh/m^3 power consumption). A detailed description of bench scale treatments and their methodology, in addition to full scale treatments, are outlined in Mundi et al. (2017).

Water quality parameters were tested using standard methods as listed in text Standard Methods for Examination of Water and Wastewater, 22nd Edition (APHA/AWWA/WEF, 2012). TS and TSS were measured using the evaporation-mass balance Method 2540 B and Method 2540 D, respectively. BOD was measured using Standard Method 5210. Additional water quality testing was conducted using the Hach instrumentation and water quality testing kits, such as COD (Dichromate Method, TNT821,2 - Method 8000), TN (Persulfate Digestion, TNT826,7,8 - Method 10208), TP (Ascorbic Acid, TNT843,4,5 - Method 10209 and 10210), and Ammonia as N (Salicylate, TNT830,1,2 - Method 10205). A Digital Reactor Block from HACHCO (DRB200-02) and Ultraviolet-Visible Spectrophotometer from HACHCO (DR5000-03) was used to complete the previously listed tests.

5.3.2 Data Analysis

The compiled master dataset was manually inspected for missing and incomplete data. Where necessary and possible, missing data was predicted using the relationships developed in Mundi et al. (2018), between similar water quality parameters. The model variables, their range, and the degree of variability in water quality parameters of wash-waters were determined statistically using r software (RStudio - Version 1.0.153).

Variable selection is a practical way to reduce the number of input variables needed to choose the optimal number of input variables for developing models. This is done to remove input variables that have no significant relationship with the output variable, which reduces the computational complexity and improves predictions (Tomperi et al. 2017). Using too many input variables can lead to an overfitted model and makes it less practical, as the collection and analysis of additional variables can be costly. Variable selection in MLR models was achieved conducting a Pearson correlation matrix, highlighting statistically significant (p-value < 0.01) correlation.

Before modeling the data, the inputs and output were normalized using a linear scaling method in Eq. (1), with a 0 to 1 scale (Thompson, 2014). Eq. (1) was used for numerical variables, such as BOD, however the normalizing of categorical variables such as process and treatment were different. The process and treatment were scaled using a ranking number, similar to Mundi et al. (2018) obtained by the ranking of average treatment reduction efficiency with respect to treatment parameter, such as BOD. Normalizing was done to prevent the magnitude of each parameter from potentially influencing the weights assigned in model development, as the dataset includes several different types of measurements.

$$z_i = \frac{x_i}{x_{max} + 1} \qquad (1)$$

Where, z_i is the normalized value computed for input i, x_i is the actual value of the input i, x_{max} is the maximum value of all input values for a given parameter.

MLR is a statistical technique used to model the relationship between two or more explanatory variables (independent) and a response variable (dependent) by fitting a linear equation into the observed data. The MLR model can be defined as:

$$y_i = \beta_0 + \beta_1 x_{i,1} + \beta_2 x_{i,2} + \cdots + \beta_k x_{i,k} + \varepsilon_i \qquad (2)$$

Where, y_i is the dependent variable, β_0 is a constant or intercept, $x_{i,k}$ is an independent variable, β_k is the coefficient regression vector or slope, and ε_i is random measured error. In the present study, r language/software (RStudio - Version 1.0.153) was used to calculate the MRL models.

ANN is a mathematical modelling technique based after brain neurons, specifically the way in which they process information and make decisions. The brain uses many senses (inputs) like hearing, touch, sight, taste, and smell to make decision using neurons about everyday tasks, such as to perform decision on driving. The function involved in calculating a decision are complex and nonlinear in nature. Similarly, in this study the ANN utilizes a large number of inputs (process, product, treatment, and influent water quality parameters) to neurons, which perform calculations using weights to produce an output/results. A schematic of the ANN structure is presented in Figure 5-2, where the three main components are highlighted: input layer (input variables), hidden layer (neurons), and output layer. The connection line used to connect the input layer nodes to hidden layer nodes has an associated weight, which highlighting the importance of each input variable.

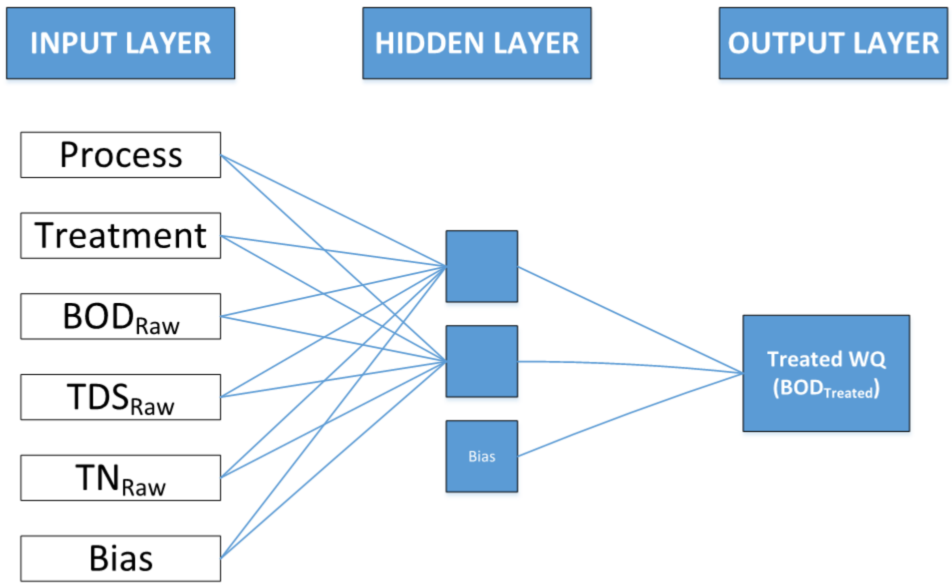

Figure 5-2: Schematic representation of the ANN structure used to produce models for predicting treated water quality parameters. Treated BOD is determined by the model based on inputs representing water quality such as BOD, TSS, TN, TP, and process/treatment and bias parameters as an example.

The training of ANN is an essential and necessary part, before it can be used to perform predictions on future events/samples. During training, the weights used to assess the inputs to generate an output, are optimized to reduce error between actual and predicted output. The weights are validated through a testing process. This study used Tiberius – Predictive Modelling Software (Brierley, 2018), which is an inexpensive and highly user-friendly ANN program that utilizes the multilayer perceptron (MLP) methodology. The algorithm consists of two steps, first the forward pass, where the predicted outputs corresponding to the given inputs are assessed. In the second step, the backward pass, the partial derivatives are propagated back through the network. This combined process is used to minimize error or optimize the gradient descent algorithm by adjusting the weight for each input, the whole process is iterated until the weights have converged. For this study 70 percent of the dataset was randomly selected for training and testing while the rest 30 percent was used for validation (Gazendam et al., 2016).

MLR models have been utilized for decades to predict linearly correlated parameters. They are easy to understand and can easily be highlighted in a mathematical equation. Meanwhile, ANN models are very powerful models that utilize the activation function which are non-linear, where the weights of the parameters are highlighted but not the function themselves. However, they also require large data sets. Exploring both methods can confirm core findings and provide a suitable model based on application.

5.3.3 Model performance evaluation

Statistical methods were used to assess the performance and validity of the developed models for treated wastewater and wash-water quality. The coefficient of determination (R^2) was used to understand the amount of observed variance within the models, Eq. (3). The root mean square error (RMSE) and mean absolute percent error (MAPE) were used to understand model accuracy and precision, Eq. (4) and (5). RMSE shows differences between the observed and predicted values in the units of the variable of study. In Eqs. (3) and (4), variables, O and P are the observed and model predicted values, respectively, and n is the number of observations. A variety of statistical measures were utilized to understand unique properties of the model performance.

$$R^2 = \left[\frac{\sum_{i=1}^{n} (O_i - \bar{O})(P_i - \bar{P})}{\sqrt{\sum_{i=1}^{n} (O_i - \bar{O})^2} * \sqrt{\sum_{i=1}^{n} (P_i - \bar{P})^2}} \right]^2 \quad (3)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (O_i - P_i)^2}{n}} \quad (4)$$

$$MAPE = \frac{100}{n} \sum_{i=1}^{n} \left| \frac{(O_i - P_i)}{O_i} \right| \quad (5)$$

5.4 Results and Discussion

In this study, for the first time the results of wastewater treatment feasibility, from bench scale testing and full scale treatment sampling, of fruit and vegetable washing and processing facilities were analyzed to develop predictive models to estimate water quality parameters of the treated wastewater. The study also used facility operating variables as input variables, such as the type of process (washing versus processing). The optimal subsets of input variables for the different models were selected using correlation analysis and statistical significance tests. The MRL and ANN modeling techniques did not consider any deterministic models, chemical, or biological knowledge about the treatment processes, and were based on mathematical grounds only. MLR and ANN have been used before, however, this study used these modeling techniques for wastewater and wash-waters treatment prediction for a wide range of fruits and vegetables. This study provides insight on three novel aspects, a new sector with respect to industrial/agricultural wastewaters, the use of bench scale testing and full scale treatment data, and the large variety of fruit and vegetable wash-waters including the utilization of process type (W versus WP).

The methods studied herein provide generalized universal solutions that are easily usable in the different studied cases. However, it is important to keep in mind that the results based solely on a mathematical analysis can be inaccurate compared to the actual situation in the wastewater treatment process, especially when applied outside the range of the model. The complexity inherent in wastewater treatment processes may highlight quasi-correlations, which may not always mean a strong real-world causality. Also, many hidden factors exist that impact the real process, but may not be shown due to the limited amount of data or measurements. Due to these challenges many researchers have not attempted to model the large variety of samples and treatments.

Before analysis, the data was prepared by transforming categorical variables to numerical values for treatment and process variable, done using ranking analysis as described in methodology. The aggregated ranks corresponding to treatment and process type (W or WP) are described in Table 5-1. The posted ranks greater than 0.75 are shaded and bolded, indicating most effective treatments, such as C&F, EC&F, and DAF for bench scale and MBR+RO+UV, POND, and SET1G for full scale. Ranks lower than 0.25 are hatched and show the least effective treatments, while the remainder of the range 0.74 – 0.26 are left blank and indicate moderate effectiveness. TSS removal was least effective for S and HC treatment compared to C&F and settling at full scale, which utilizes chemicals and long settling time, respectively. Similar conclusions can be drawn for other water quality parameters from Table 5-1. Some key observations show that MBR was the best overall, this was no surprise as MBR treatments produce the highest quality waters regardless of the type of wash-water or process. However, MBR are energy intensive, require long start up times, and are very sensitive to changes in wastewater feed. EC&F and C&F show a good reduction across many water quality parameters. Full scale treatments with pond, settling with grasslands, and settling with 3 tanks in series (POND, SET1G, and SET3) were capable of reducing solids effectively, under the right conditions (flow, concentrations, and settling time).

Table 5-1: The developd ranks represent ability of treatment to be effective, ranked best (1) to worst (0). Ranks greater than 0.75 are shaded and bolded and ranks lower than 0.25 are hatched, while the remainder of the range 0.74 – 0.26 are left blank, for visual aid. The ranking for process is also provided.

		$TSS_{Treated}$		$TP_{Treated}$		$TN_{Treated}$		$COD_{Treated}$		$BOD_{Treated}$		$NH4\text{-}N_{Treated}$	
	Process\ Treatments	W 1	WP 0.5	W 1	WP 0.5	W 1	WP 0.5	W 1	WP 0.5	W 1	WP 0.5	W 0.5	WP 1
Bench Scale	C	0.55	0.70	0.11	0.29	0.44	0.14	0.33	0.29	0.33	0.13	0.33	0.14
	DAF	0.73	**0.80**	0.67	0.43	0.67	0.29	0.56	0.43	0.22	0.25	0.44	0.29
	EC&F	0.45	0.60	**1**	0.57	**0.78**	0.57	**0.89**	**0.86**	0.56	**0.75**	0.56	0.71
	C&F	**1**	**0.90**	0.44	**0.86**	0.56	0.43	0.67	0.63	0.44	0.5	0.22	0.38
	HC	0.27	0.50	-	-	-	-		-	-	-	-	-
	S	0.09	0.10	-	-	-	-	-	-	-	-	-	-
Full Scale	MBR+RO+UV	-	**1**	-	**1**	-	**1**	-	**1**	-	**1**	-	**1**
	POND	0.18	0.40	**0.89**	-	**0.89**	-	0.22	0.14	**0.78**	0.38	**0.89**	0.57
	SET1	0.36	0.30	0.33	0.71	0.33	**0.86**	0.44	0.57	**0.89**	0.63	**0.78**	**0.86**
	SET1G	**0.91**	-	**0.78**	-	**1**	-	**0.78**	-	**1**	-	0.67	-
	SET3	**0.82**	0.20	0.22	0.14	0.22	0.71	**1**	0.71	0.67	**0.88**	**1**	0.43
	SETBIO4	0.64	-	0.56	-	0.11	-	0.11	-	0.11	-	0.11	-

Process: Washing (W) versus Washing and Processing (WP).
Treatment: Bench scale treatments include screening (S), hydrocyclone (HC), settling with coagulation and flocculation (C&F), dissolved air flotation (DAF), centrifuge (C), and electrocoagulation (EC&F). Full scale treatments sampled included a single tank settling (SET1), settling followed by open grass (SET1G), three settling tanks in series (SET3), sequential batch reactor with four stages – settling, aeration, nutrient removal, settling (SETBIO4), and membrane bioreactor with reverse osmosis and UV disinfection (MBR+RO+UV).

There are some differences between W and WP within the same water quality parameter and treatment, for example, C&F for $TP_{Treated}$ show, good effectiveness for WP but not so great for W type processes. Some process types and water quality parameters were not part of the study, such as the W type wash-waters for MBR. The missing water quality parameters for S and HC treatments were not collected since these treatments are least likely to impact TP, TN, COD, BOD, and NH_4-N, as shown in the literature. The ranks in Table 5-1 require substitution into the MLR equations (Table5) for estimating treated water quality parameters.

After converting all data to numerical values, it was assessed for Pearson correlation analysis, highlighting statistically significant (p-value < 0.01) correlations, and are presented in Table 5-2. Correlation analysis is a valuable tool in identifying correlations between water quality parameters, process, treatments, and dependent variables. More importantly, it shows which input parameters have a good relationship with the dependent variable.

Table 5-2: The correlation matrix highlighting which parameters show good linear relationship that can be used for MLR and/or ANN to select and test input variables. Shaded vaues show the strong correlations, while the rest show weak correlations.

	Process	Treatment	pH_{Raw}	BOD_{Raw}	COD_{Raw}	$NH_4\text{-}N_{Raw}$	TN_{Raw}	TP_{Raw}	TSS_{Raw}	TS_{Raw}	TDS_{Raw}
$TSS_{Treated}$	-0.08	-0.42	0.02	-0.04	0.16	0.05	0.22	0.13	0.24	0.32	0.05
$BOD_{Treated}$	-0.53	-0.29	-0.2	**0.9**	**0.62**	0.09	0.36	0.04	0.05	0.28	**0.61**
$COD_{Treated}$	-0.58	-0.26	-0.11	**0.65**	0.56	0.07	0.19	-0.01	0.04	0.40	**0.62**
$TP_{Treated}$	-0.55	-0.35	-0.19	0.07	0.16	0.48	0.19	**0.88**	0.08	0.07	0.02
$TN_{Treated}$	-0.23	-0.43	0.17	0.34	0.49	0.58	0.50	0.40	0.10	0.27	0.35
$NH_4\text{-}N_{Treated}$	-0.13	-0.46	-0.07	0.18	0.41	**0.85**	0.37	0.27	0.56	0.14	-0.05

The variables with significant relationship were selected for use in MLR and ANN. This statement is true for most parts, except for process, this was used for all MLR and ANN models strictly to allow comparison, and possible relevance in ANN models. Reduction of the input variable and variable selection is important as efforts (complexity and computation power) are needed to generate models. A minimal set of input variables were used to make the models more practical, useful, and easy to understand. Modeling all nine water quality parameters can produce long and complicated equations, not to mention the risk of producing overfitted models.

Table 2 shows dependent variables, which are the outputs of the model, and the potential input variables shown in the columns. The shaded values represent good correlation while white cells show neutral or weak correlations. Treatment was relevant for most water quality parameters, however, for $BOD_{Treated}$ and $COD_{Treated}$, the process was more relevant, suggesting treatments may not be effective. Many core raw water quality parameters were relevant as expected, which are defined as for example, BOD_{Raw} being the core parameter for $BOD_{Treated}$ model to predict effluent water quality. The correlations were weak for the $TSS_{Treated}$ model, as the highest correlation was observed to be 0.32 with TSS_{Raw} and lowest was 0.08 with process type. These correlations were used as the basis for selecting the different input parameters for the MLR and ANN models.

The range for wash-water quality and treated water quality parameters are shown in Table 5-3, highlighting the minimum, maximum, and the average values of the inputs and outputs used for the different models. Disposal of wastewater and wash-water requires a meeting of the listed regulatory standards, also shown in Table 5-3. To meet drinking water standards, TP and NH_4-N, require 99% reduction when measuring from the average raw wash-water/wastewater. To meet the sewer limits TSS is required to be reduced by 85% from the mean raw wash-water/wastewater. To release wash-water/wastewater to a stream, over a 99% reduction of TP is needed. The selected inputs for different models are highlighted in Table 5-4, presented and discussed later.

Table 5-3: Model input and output parameters and their minimum, maximum, and mean values.

Raw Wash-water Quality Parameters	(mg/L)	TSS_{Raw}	TDS_{Raw}	TS_{Raw}	COD_{Raw}	BOD_{Raw}	TN_{Raw}	TP_{Raw}	$NH_4\text{-}N_{Raw}$
	min	24	364	468	20	5	0.9[a]	1.30	0.09
	mean	2,498	1,532	3,795	1,556	387	15	16.5	3.1
	max	42,920	8,740	13,855	12,400	3,760	101	179	35[b]
Treated Wash-water Quality Parameters	(mg/L)	$TSS_{Treated}$	$COD_{Treated}$	$BOD_{Treated}$	$TN_{Treated}$	$TP_{Treated}$	$NH_4\text{-}N_{Treated}$		
	min	0	2	2	0.03	0.04	0		
	mean	452	632	177	9.4	5.6	4.5		
	max	7,160	8,300	2,300	53.1	90	70		
Effluent requirements for wastewater discharge in Canada	(mg/L)	TSS	TDS	TS	BOD	TP	NH4-N		
	Drinking Water[c]	-	500	-	-	0.01	0.02[g]		
	Sanitary /Sewer Discharge[d]	350	-	-	300	10	-		
	PWQO[e]	25[f]	-	-	20[f]	0.02			

[a]For $TN_{Treated}$ model lower limit for TN is 2.5 mg/L
[b]For $NH_4\text{-}N_{Treated}$ model higher limit for NH_4-N is 105 mg/L
[c]Data obtained from Supporting Document for Ontario Drinking Water Quality Standards, Objectives and Guidelines, Tables 1, 2, and 4
[d]Data obtained from City of Toronto Sewer Discharge and Storm Water Discharge Limits, Table 1
[e]Data obtained from Provincial Water Quality Objectives for Surface Water, some parameters are subjected to additional conditions
[f]Limits for effluent discharged to receiving waters; Guidelines for Effluent Quality and Wastewater Treatment at Federal Establishments
[g]Additional requirements related to pH

Looking at Table 5-3 it is evident that the ranges of water quality parameters are highly variable as many different types of wash-waters were studied. The maximum value for TSS_{Raw} stands out as it is very high, even compared to the maximum TS_{Raw} value. This is because the TS_{Raw} value corresponding to this high TSS_{Raw} value was not available for some samples, as such was predicted using Mundi et al. (2018). Some of the past data from other datasets only measured limited or different water quality parameters, this was a major challenge, as some data points had to be excluded for some models. As a result, some models have lower sample numbers compared to others, see Table 5-4.

The key findings of the study, that is the ability to predict treated water quality based on treatment, process, and raw wash-water quality parameters, are highlighted in Table 5-4. The table shows a number of samples used to construct the models, training was 70 %, while test/validation was 30 % of the total samples and the selected input parameters. Along with quality and performance parameters of the two different modeling methods, such as the coefficient of determination (R^2 - %), residual mean standard error (RMSE - mg/L), and mean absolute percent error (MAPE - %).

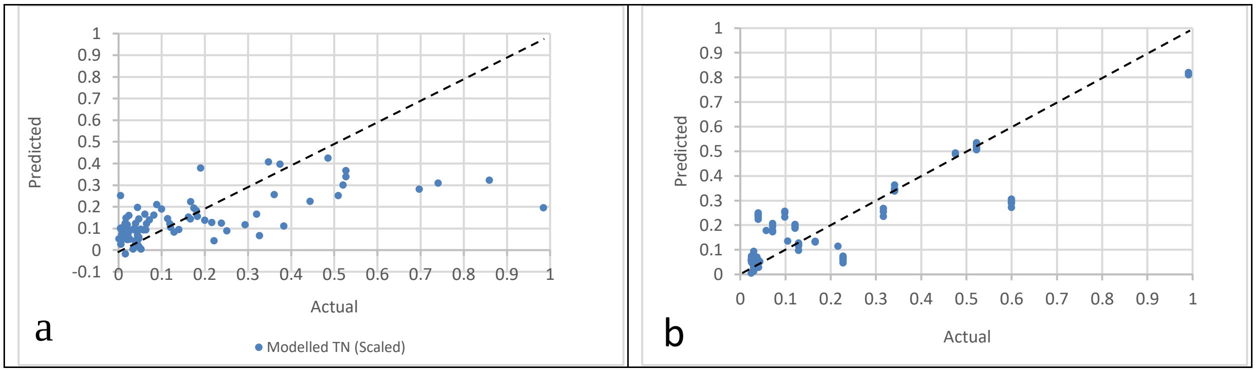

Figure 5-3: Actual versus predicted data plots are shown for $TN_{Treated}$ model for MLR (a) and ANN (b) for comparison. The MLR predictions are scattered while the ANN predictions are grouped.

A total of six water quality parameters were analyzed for MLR and ANN as shown in Table 5-4. The greatest improvement was made for the $TSS_{Treated}$ model, where ANN significantly improved the prediction, from R^2 of 30 % in MLR to 63 %, while NH_4-$N_{Treated}$ was only improved by 10 % using ANN method. The R^2 improved for all six water quality parameters, while the RMSE and MAPE went up with the use of the ANN modeling method. This was interesting and highlighted the need to observe the modeled and actual data in detail. As such, Figure 5-3 was generated showing plots of the actual versus modeled data plots of $TN_{Treated}$ for both MLR and ANN for comparison. Figure 5-3 (a) ANN and (b) MLR show a key difference, that is the predicted values in the MLR model are consistently off from the actual values. While in the ANN model the values seem to be grouping together and are either correct or completely off compared to the actual values. This is linked to the increased RMSE and MAPE under ANN models.

Also, large data is grouped at the lower level of $TN_{Treated}$ indicating some skewness, as such the user must take extra care when predicting very low and very high values, while the prediction around the mean is suitable and correct. Another important observation in the $BOD_{Treated}$ model showed overfitting of the ANN model when BOD_{Raw} was used in addition to TDS_{Raw}, TN_{Raw}, and process for the ANN models. The results were fine when used in the MLR model, but not for ANN model, as the model was overfitted, as shown by the extremely high R^2 value of 99 % and the low value of 2 mg/L for RMSE and MAPE. Thus, moving forward the core raw parameters were not used in some models, as it leads to overfitting of the models. This phenomenon was observed for $BOD_{Treated}$, $COD_{Treated}$, $TN_{Treated}$, $TP_{Treated}$, NH_4-$N_{Treated}$.

Table 5-4: Models generated for treated water quality parameters showing the input variables used and their corresponding R^2 and RMSE values for train and validation datasets.

Number of Samples	Model	Model Set	Model Parameters	MLR	ANN	Change in
122	$TSS_{Treated}$	Train	Input Variables*	3,6,10,11	3,6,10,11	0
			R^2 (%)	30	63	+33
			RMSE (mg/L)	736	947	+211
			MAPE (%)	65	278	+213
46		Validate	R^2	54	71	+17
			RMSE	706	744	+38
			MAPE	364	1,038	-674
			Architecture**		4-3-1	
120	$BOD_{Treated}$	Train	Input Variables*	2,5,6,10,11	2,5,6,10,11	0
			R^2	83	99	+16
			RMSE	159	2	-157
			MAPE	558	1	-557
52		Validate	R^2	67	99	+32
			RMSE	199	2	-197
			MAPE	443	1	-442
			Architecture**		5-1-1	
62	$TP_{Treated}$	Train	Input Variables*	7,8,10,11	8,10,11	-1
			R^2	59	88	+29
			RMSE	6.4	12.1	+5.7
			MAPE	58	140	-82
28		Validate	R^2	80	70	-10
			RMSE	12.8	5.5	-7.3
			MAPE	63	196	-133
			Architecture**		3-1-1	
57	$TN_{Treated}$	Train	Input Variables*	2,6,8,10,11	2,8,10,11	-1
			R^2	58	70	+12
			RMSE	7.6	5.6	-2
			MAPE	68	84	+16
29		Validate	R^2	70	84	+14
			RMSE	10.9	6.9	-4
			MAPE	93	110	+17
			Architecture**		4-2-1	
112	$NH4\text{-}N_{Treated}$	Train	Input Variables*	1,8,10,11	1,10,11	-1
			R^2	83	93	+10
			RMSE	6.0	3.4	-2.6
			MAPE	1065	2162	+1,097
49		Validate	R^2	71	83	+12
			RMSE	7.4	9.7	+2.3
			MAPE	1,138	1,307	+169
			Architecture**		3-2-1	
123	$COD_{Treated}$	Train	Input Variables*	2,4,10,11	2,5,10,11	1
			R^2	54	73	+19
			RMSE	890	1,100	-890
			MAPE	820	125	-59
54		Validate	R^2	73	70	-26
			RMSE	575	1,530	+466
			MAPE	943	116	-55
			Architecture**		4-2-1	

*Input Variables – Water quality, process, and treatment parameters:
1 – TSS, 2 – TDS, 3 – TS, 4 – COD, 5 – BOD, 6 – TN, 7 – TP, 8 – NH4-N, 9 – EC, 10 – Treatment, and 11 – Process
**Input-Hidden-Output layers are indicated.

Overfitting happens when a model learns the data details and noise in the training data that negatively impacts the performance and the models' ability to generalize. Overfitting usually occurs with nonparametric and non-linear models such as ANN. In this case combination of both data details and noise, as some treatments had few experiments or single samples for full scale treatment, and due to the high variability of the data given different wash-water types and processes. Underfitting can also occur when the data does not show strong correlations or does not show a strong fit to linear functions. Some underfitting is evident in MLR models as seen for $TSS_{Treated}$ MLR model, where the R^2 is 30%, very low. The RMSE and MAPE show the magnitude and percentage of accuracy for each type of model. For $TSS_{Treated}$ model the RMSE and MAPE are generally very high as the model is based on highly variable data sets, as such the accuracy of the TSS model is quite low.

$TP_{Treated}$ and $TN_{Treated}$ models showed similar results as shown by the change from MLR to ANN in terms of R^2. TP model was improved by 29 % while the $TN_{Treated}$ model was only improved by 12 % points with respect to the R^2. $TP_{Treated}$ models used TP and NH_4-N in addition to treatment and process. However, this was not the case for $TN_{Treated}$ due to overfitting as mentioned before. The RMSE for all models for $TP_{Treated}$ and $TN_{Treated}$ was in the range of 5.5 to 12.8 mg/L, which is reasonably good, given the variability in wash-water data points. The RMSE for $TP_{Treated}$ train models increased from MLR to ANN, and similarly, the R^2 reduced for ANN model for the $TP_{Treated}$ validate data set, which are unusual. The NH_4-$N_{Treated}$ model also showed significant improvement from MLR to ANN methods, as indicated by R^2 increasing to 93 % from 83 %. While the RMSE ranged from 3.4 to 9.7 mg/L for both model types. The MAPE ranges from 50 – 196 % for all models of $TP_{Treated}$ and $TN_{Treated}$, reflecting the low quality of model accuracy which is attributed to the low number of samples and the highly variable data set. While for NH_4-$N_{Treated}$ ANN model the MAPE is extremely high indicating the model does not fit well over the data.

The $COD_{Treated}$ model also showed some improvement with ANN methods with R^2 increasing to 73 % from 54 %. The $BOD_{Treated}$ model improved by 16 % as indicated by the R^2, however, as mentioned before seems to be overfitted for ANN. The overall trends show that ANN methods can provide better prediction than MLR methods, as shown by the improved R^2 for some of the developed models.

However, a fine balance is required between the number of input variables selected for models and the risk of overfitting. Given the challenges of the diverse and breadth of the samples and experiments studied, the models were still able to capture and show generalized solutions. This was due to the ability of the ANN to capture non-linear relationships better than MLR methods. However, the large RMSE and MAPE observed for some models can make it challenging to assess the predicted effluent water quality parameters against regulations for effluent release, which are typically very low, see Table 5-3. In general, it is evident that both, MLR and ANN methods are feasible in determining the treated water quality of wash-water/wastewater from the fruit and vegetable industry as highlighted here. MLR is a great modeling method as it provided insight into the impact of coefficients of the input parameters, while ANN provides greater accuracy but is a black box model with no insight. A high degree of variability exists, which is expected due to the non-linearity of the input variables. Another major challenge is that of large data sets, which are often required for ANN models, however, this was not the case for this study, where many different wash-waters were studies under many different treatment scenarios. Modeling is best suited for single treatment with a large dataset. This study attempted to formulate a universal model, that can be seen as very challenging, due to the high level of error in some models as shown by MAPE and RMSE. However, the models can be improved by collecting additional data.

The MLR equations are presented in Table 5-5. All equations have a positive intercept followed by negative treatment coefficient, followed by positive process coefficients for most models, while the rest of the coefficients show both positive and negative values. The process coefficients are negative for some models because their ranking for W and WP process is different for each model. The worst conditions were represented by the lower rank of 0.5 equivalent to the WP process and for other water quality parameters it was equivalent to W process. The parameters TN_{Raw}, TDS_{Raw}, and NH_4-N_{Raw} were most prevalent in the developed models. The magnitude and negative or positive value of the coefficient determine the level of effect on the predicted parameter.

Table 5-5: MLR equations for predicting treatment effluent water quality of wash-water treatments

MLR Equations	Equation Number
$TSS_{Treated} = 0.095 - 0.191(Treatment) + 0.011(Process) + 0.136(TS_{Raw}) + 0.131(TN_{Raw})$	(3)
$BOD_{Treated} = 0.013 - 0.043(Treatment) + 0.025(Process) - 0.031(TDS_{Raw}) + 0.563(BOD_{Raw}) - 0.006(TN_{Raw})$	(4)
$COD_{Treated} = 0.237 - 0.169(Treatment) - 0.172(Process) + 0.270(TDS_{Raw}) + 0.166(COD_{Raw})$	(5)
$TP_{Treated} = 0.035 - 0.069(Treatment) - 0.172(Process) + 0.318(TP_{Raw}) + 0.282(NH_4{-}N_{Raw})$	(6)
$TN_{Treated} = 0.1202 - 0.236(Treatment) + 0.059(Process) - 0.311(TDS_{Raw}) - 0.07(TN_{Raw}) + 0.620(NH_4{-}N_{Raw})$	(7)
$NH4 - N_{Treated} = 0.090 - 0.090(Treatment) - 0.034(Process) - 0.597(TSS_{Raw}) + 1.274(NH_4{-}N_{Raw})$	(8)

These MLR models/equations provide a simple, convenient, and practical way to determine treatment effectiveness of the particular wash-waters, which can be utilized by producers/growers to assess for potential treatment to manage and reuse wash-waters. For example, $BOD_{Treated}$ can be determined by first selecting Eq. 4 in Table 5-5, then obtaining the applicable treatment and process variables from Table 5-1, which will be multiplied by their corresponding coefficients. The TDS_{Raw}, BOD_{Raw}, and TN_{Raw} are then plugged into the models for the wash-water/wastewater to be predicted. Once all the values are obtained, they are then entered into the $BOD_{Treated}$ model, Eq. 4 found in Table 5-5. The calculated answer can be used along with corresponding RMSE and MAPE to assess treatment reduction/effectiveness.

To illustrate the use of the $BOD_{Treated}$ model, wash-water with TDS of 475 mg/L, COD_{Raw} of 165 mg/L, process type of W and undergoing EC&F treatment would have $BOD_{Treated}$ of 60 mg/L. First, the numerical parameters are normalized, for TDS_{Raw}, 475 is divided by the max value of TDS_{Raw} (from Table 5-3) plus one, 475/(8,740+1), which equals 0.0545. Similarly, COD_{Raw} is normalized, and the value is 0.0133. The next step is to look up process value for W type process from Table 5-1 for $BOD_{Treated}$ model, which is 1, also for EC&F treatment, which is 0.56. The next step is to substitute the values into Eq. (4) from Table 5-5 to calculate $BOD_{Treated}$. In some cases, the calculated value could be negative, given the linear relationship, and should be converted to 1 for simplicity. The equations of MLR and ANN are summarized and integrated into an easy to use Microsoft excel worksheet tool. The user can input the raw wash-water values and obtain a comparative analysis of treated effluent for all treatments at once. The predicted values for each treatment are then compared with regulated effluent limits to understand which treatment is most capable of meeting the standards. The worksheet also incorporates some cost analysis for the different treatments studied to provide cost/benefit analysis.

The developed models complement the treatment decision matrices/tables produced in Mundi et al. (2017) that show the level of treatment expected from various wash-waters/wastewaters. The decision matrices/tables provided a range for treatment effectiveness, while these models extend that analysis to numerical models for more flexible treatment predictions. Some limitation exists, such as over and underestimating of treated water quality parameters due to under and overfitting of the models. However, prediction of treated water quality levels is still valuable, and the methods demonstrated herein can be implemented by facilities for continuous monitoring and treatment selections. This information is valuable for farmers, governments, engineers and consultants, and other stakeholders in determining wash-water treatment and sizing, understanding treatments capable of meeting regulatory standards, and treatment costs from predicted water quality parameters. The study was successful in capturing a wide variety of information and concatenating into a useful tool for making an important decision on treatment of wash-waters/wastewaters, which previously did not exist.

5.5 Conclusion

The study highlighted the use of novel MLR and ANN techniques to model fruit and vegetable washing and processing wastewaters treatments in predicting treated water quality parameters. These universal models successfully captured data from many different commodities representative of post-harvest processing including fresh-cut industry. Modeling a wastewater treatment process is difficult to accomplish due to the high non-linearity of the treatments studied and the non-uniformity and variability of wash-water/wastewaters as well as the nature of the chemical/biological reactions occurring in treatments. An MLR model approach was assessed to understand any linear relationships and the ANN models for understanding interdependency between outputs and inputs involving non-linear relationships.

The models developed for estimating treated parameters from bench scale and full scale treatments include $TSS_{Treated}$, $BOD_{Treated}$, $COD_{Treated}$, $TN_{Treated}$, $TP_{Treated}$, and $NH_4\text{-}N_{Treated}$ water quality parameters. The derived models performed very well as indicated by R^2 values. The RMSE performance parameter indicates the expected error boundaries, which is in the range of acceptable. The variability is inherent to the developed models, as the datasets were a combination of lab and industry-wide samples, and may be improved by increasing sample size for various sets, such as for full scale treatments. Combination of data types, number of samples, the variability of the different wash-water types, and noise within the data influence the quality of the models. The balance between a number of input variables selected for modeling and risk of over or underfitting is very important.

Previous research did not consider the holistic approach presented in this study, for predicting different fruit and vegetable wastewater treatments. As such, this study examined 14 different facilities (Apple, Carrot, Potato, Ginseng, and others) and 13 different wash-waters/wastewaters treatments for treatment effectiveness of TSS, TN, TP, NH4-N, COD, and BOD water quality parameters. MLR models were a great tool for predictions as it provided insight into the impact of input parameters through its coefficients and showed consistent error over all treatments. ANN was more flexible and better captured the results but showed extreme or zero error terms for some samples. These novel MLR and ANN models can be used for the design of wash-water treatment systems and provide a list of treatment options.

5.6 Acknowledgements

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Chapter 6: Economic Analysis

Chapter 6 highlights the economic analysis, which is used to determine whether a project is feasible or not. Capital costs include the cost of equipment while operating costs include the cost of water and wastewater services, electricity, chemical, pH control, operator, annual debt service, etc. All costs or benefits are assessed in term of their monitory value or loss. Capital costs can vary significantly as shown, thus using financial loan analysis of 20-year amortization period at 8% provides for an annual debt service amount, which is normalized to the annual design/facility flow. Allowing for capital cost to be presented, for ease of use, in dollar per cubic meter of water treated ($\$/m^3$). Challenges in determining costs are also noted. The analysis can be used to better understand potential capital and operating costs associated with wash-water/wastewater treatment and reuse.

6.1 Introduction

Engineering economic analysis focuses on costs, revenues, and qualitative benefits that take place over the course of the project's life. It is needed to asses any problem, in this case selecting a wash-water or wastewater treatment process that has financial aspects required to reach an important decision. Cost and benefit analysis are important to consider in water and wastewater treatment projects as a heavy capital investment are often required, thus all benefits/costs need to be considered in detail. This section will highlight a brief economic analysis which outlines the different types of costs to consider, such as operating and capital costs, including chemical, pumping, and electrical costs, associated in employing technologies for pre-treatment of wash-water for reducing solids loading, and/or implementing water reuse.

Trends in utility costs such as water, wastewater, and electricity are highlighted by linear equations produced from historical data. This can help in understanding future costs/benefits of water and electrical energy. Results are tabulated and show information on pH adjustment and coagulant costs, noted in dollar per cubic meter ($\$/m^3$) of treated waters. Potential annual coagulant costs, for the studied facilities, are calculated to show the range of operating costs expected for use with physiochemical treatments. Treatment capital and operating costs are summarized as the dollar cost of treating cubic meter of water. The $\$/m^3$ or unit costs are easily comparable between different treatments, over a normalized flow, and show approximate costs involved in implementing treatment systems. The savings resulting from water/wastewater rates, surcharges, and bulk water delivery may be incorporated.

The capital costs can include the cost of acquiring engineering and installation services, which are often coupled with equipment cost. The operating costs include utility costs, such as water, wastewater, and electricity (hydro) services, pH adjustment (if needed), and coagulants, maintenance, operator, and laboratory services for water quality testing. Capital costs can be high, but the benefits include reduced overall water consumption and disposal costs. For example, reducing or eliminating BOD and TSS surcharges, where applicable, based on location and municipality, can result in significant cost savings.

Environment and water resources protection are difficult to include in the cost-benefit analysis, as they cannot easily be assessed for their monetary value and their long-term benefits are often overlooked. However, water is very precious to both the environment and its inhabitants, including humans, thus it is important to consider all risks to present and future water sources.

The risk associated with releasing low quality/untreated wash-water/wastewater into the environment can be great, as groundwater, streams, rivers, lakes, and soils may be contaminated leading to degraded water resources for other users/ecosystems within watersheds. Groundwater is our most important source of fresh water for drinking, irrigation, and industrial/commercial applications. Lakes can be impacted by high nitrogen and phosphorus loadings, which lead to eutrophication (algal blooms) resulting in reduced oxygen in the water. Irrigation of low quality/untreated wash-water/wastewater may impact the soils ability to be fertile, the dissolved salts can create toxic conditions for plants to grow. It is important to protect these sources and pathways of contamination, as their remediation may be very costly or irreversible.

To reduce the environmental impact and the aforementioned risks, the specified discharge regulation set by municipal/federal government need to be met. Rural and farm areas may be particularly susceptible to the above mentioned environmental impacts by discharging low quality/untreated wash-water/wastewater into the environment. To reduce or eliminate the adverse effect, wash-water/wastewater treatment and reuse systems are necessary, and the benefit to the environment overweighs the cost of the treatment. There are many challenges in quantifying the positive impact on the environment and putting a price on the environment. A life-cycle cost analysis may be used, as it accounts for all factors involved from conception to production to end of life disposal cost, including environmental impacts, however, this was not part of this study.

Before starting the economic analysis, it is important to consider in detail the potential uses of the recycled water in terms of quality, quantity, dependability, safety, and cost. Collection of some background information is needed to assess feasibility, such as applicable regulations regarding water quality and food safety (Asano and Mills, 1990). The steps needed in the gathering background information should start with a listing of equipment and map of the facility, pointing out the sources of fresh water, wastewater, potential points of interception for water treatment, and where the reclaimed water would be used, including flow, volumes, and water quality parameters. This would allow the creating of inventory of potential uses of reclaimed water within the facility. Essentially creating an inventory of flows and volumes. It is also important to note potential points of cross-contamination, which might already have been completed for food safety and quality assurance. Grouping the different stages of processing within a facility, such as soil washing, cutting, peeling, packaging, sanitization stages by volume and quality of water used, water quality going into the process and water quality leaving the process will assist with the process.

It is also important to determine public health and food safety requirements by consulting with regulatory agencies and by studying by-laws and regulation available online. This is done by collecting background information, the level of treatment necessary to achieve the quality of water needed for different stages of the washing and processing operations. For example, simple practices include the requirement to use potable water for final rinsing and to take appropriate measure to protect food safety from cross contamination from workers, machinery, storage bins, etc. Also, consideration for water recycling via irrigation or supplementing to natural areas, such as wetlands may also be considered. The steps listed above, used to obtain primary information are very important and are needed before cost/benefit analysis can be considered

Facilities exploring water recycling may incorporate principle concerns regarding implementation and feasibility (Anderson, 2003; Asano, 1998). Some common concerns may include the following: the price of reclaimed water may be too high relative to freshwater costs, inability to finance projects, water quality and quantity concerns, employee and consumer exposure to potential health hazards, possibly of backlash from employees, and consumer health and wellbeing protection groups, lack of reliable recycled water supply, water supply costs are insignificant compared to the inconvenience of using reclaimed water, and liability and lawsuits (Asano et al., 2007). While these concerns are real and can impact the bottom line of the business, it is important to note that using the right expertise, design, equipment, and controls, it is possible to produce safe water for food washing and processing needs.

It should be noted that the use of equipment/technology for water treatment systems/trains are based on pre-treatment of solids. Reduction in solids will also aid in reducing BOD, TP, TN, E.coli, and other contaminants, as they are often bounded to the solids or exist as a result of solids. The analysis provided herein has not been validated at full scale and thus may require additional equipment/optimization increasing or decreasing the estimated costs. Advanced treatments utilizing ultra and micro membrane filtration, reverse osmosis, ion exchange, and disinfection (UV/H_2O_2 or Ozone/H_2O_2) are necessary to provide double barrier approach to water treatment and to provide potable quality standard waters. An optimized treatment system/train can consist of (1) screening large objects and solids, using a mesh screen, settling and/or hydrocyclone, (2) pre-treatment technology (settling with C&F, DAF, centrifuge, electrocoagulation), (3) polishing (filtration) and disinfection (chlorination, UV/H_2O_2 or Ozone/H_2O_2 disinfection for double barrier approach). Polishing may be achieved using sand filters, as they are widely used in the conventional treatment of drinking water before chlorination.

6.2 Water and Wastewater Costs

Water is an essential input resource in vegetable and fruit washing and processing operations. Water taking and disposing of in urban areas is dictated by water and wastewater discharge rates levied by municipality on the users, like industry and the public. Water and wastewater rates vary depending on the municipality, for example, Region of Peel rates are cheaper than the City of Guelph. The users are charged per cubic meter of water used and disposed of, e.g., \$ 1.72 and 1.32 per m^3 for water taking and \$ 1.84 and 0.99 per m^3 for wastewater rate, for City of Guelph and Region of Peel, respectively (Region of Peel, 2017; City of Guelph, 2017). These fees are in addition to the daily service charges that apply based on water service line diameter. Figure 6-1 shows the combined water/wastewater rates ($\$/m^3$) for surrounding regions and cities. The Region of Waterloo (4.91 $\$/m^3$) and City of Guelph (3.56 $\$/m^3$) have some of the highest water/wastewater rates compared to Region of Peel (2.31 $\$/m^3$) or City of Toronto (2.66 $\$/m^3$). Additional charges for facilities exceeding set BOD, TSS, TP, TKN by-law limits in their waste stream are levied 0.64, 0.70, 2.24, 1.43 \$/kg, respectively (City of Toronto, 2018a, 2018b). Existing and current data on water rates show that water costs are increasing rapidly for some regions and cities, for example, Region of Peel had an increase of \$ 0.55 over the last 5 years, while this rate hike has been much less steep for the last two years at \$ 0.10 as shown in Figure 6-2.

Using historical data, a trend line was constructed to generate an equation for forecasting future water rates. Two separate trend lines were derived, one for the last 5 years, which was a very rapid increase, and the second trend line for the last 2 years, which shows a lower rate of increase in water/wastewater rates. An average of the 2-year and 5-year trends is also calculated and shown, this serves as a conservative estimate for the next 20 years and may be used for cost/benefit analysis. The projected rates for 2038 (20 years) for the Region of Peel may range from 3.25 – 4.52 $/m^3, with an average estimate of 3.89 $/m^3 as a conservative measure.

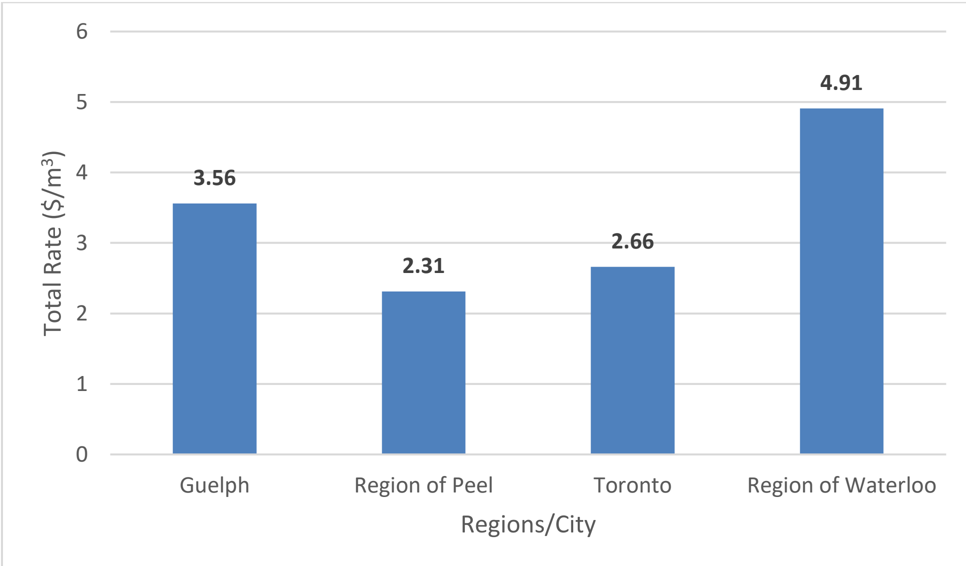

Figure 6-1: Combined Water/Wastewater Rates for 2018

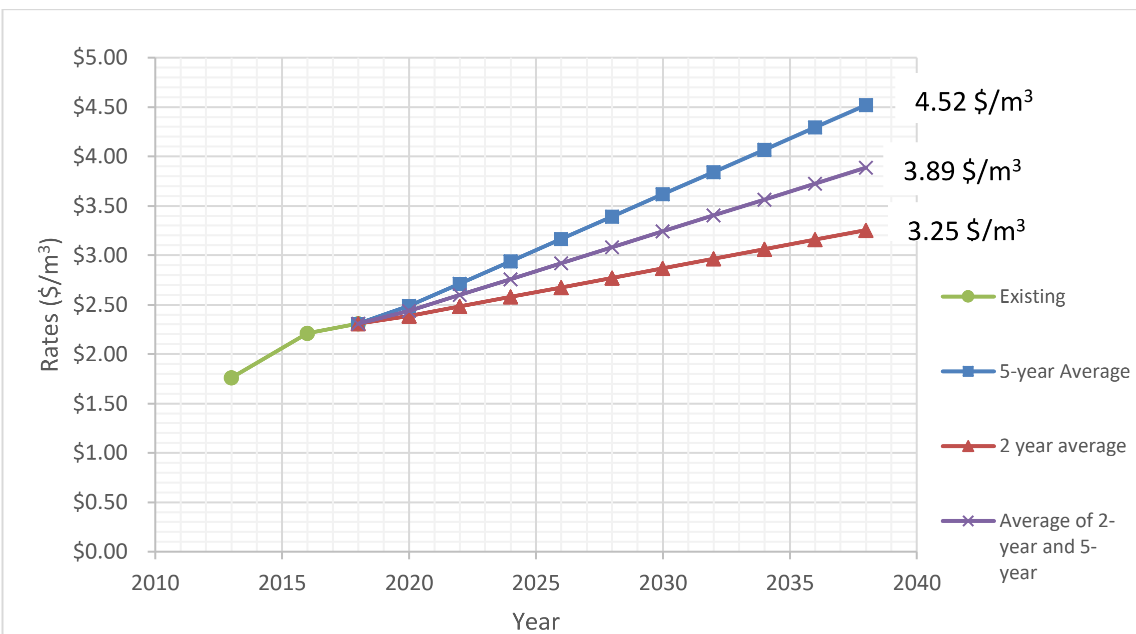

Figure 6-2: Projected future costs of combined water and wastewater rates

Overcharges can occur for exceeding set BOD and TSS limits for the wastewater stream. This cost is approximately 0.62 and 0.60 $/kg for BOD and TSS, respectively, for the City of Toronto (Stantac, 2012). Water taking and wastewater disposal rates increase 5 to 10 % per annum depending on municipality (Region of Peel, 2017; City of Guelph, 2017). The Region of Peel has experienced an increase in combined water and wastewater surcharges by about 30% over the last five years, which is significant and should be considered in cost/benefit analysis.

Whereas, rural areas, including farms, have water permits which are far less costly versus urban areas. Groundwater wells provide the fresh water needed for rural and farm operations. Ministry of Environment and Climate Change is responsible for issuing water permit ($3,000), which allows for 50,000 L/day or more of fresh water uptake, anything less can be exempted (MOECC, 2017). Availability of fresh water can be a concern for rural processors during dry periods of hot summer months. This can impact water uptake flow and volumes which can delay processing and affect production. If needed, bulk water delivery services can be acquired, which cost approximately $150 for 15 m^3 of fresh water, or 10 $/$m^3$. The reason for such a high price is due to delivery charges. The cost savings for rural processors can be difficult to see, but water reuse can offer the security of water resource for processing needs, which cannot be quantified monetarily and reduce reliance on groundwater.

Facility A1 (apple washing and juicing) is using an MBR system to reuse their water, as a result, do not require groundwater for their process needs. When and if additional water is needed, it must be trucked in through bulk water delivery service. Farms must manage the wastewater and other waste material on-site, require costly shipping to the local landfill, and/or appropriate treatment/management. With stringent regulations in place for wash-water and wastewater disposal, rural processors require adequate treatment that is cost-effective. The benefits may seem evident, such as reduced environmental impact and reduced dependence on groundwater resources, which can be overlooked due to the challenges in quantifying benefits in terms of dollar value. As in the case of Facility A1, which were focused on the long-term goals of water independence and security, and thus, decided to measure the benefits quantitively.

6.3 Electricity Costs

Electricity can be a significant operating cost for powering a water treatment train, equipment, monitoring, and control processes. The cost of electricity is dependent on region, cost of producing and delivering energy, and government policies. The electricity rates in Ontario in the last decade have been volatile, increasing since 2008 with the rapid increase in rates from 2014 to 2016, and then falling from 2016 to 2017 due to government interventions. These trends are illustrated in Figure 6-3, which shows the historical Time-of-use (TOU) rates and their prospective trend equations (Ontario Energy Board, 2017). Trend equations can be used to estimate future electricity rates. Current rates are 6.5, 9.5, and 13.2 cents per kWh for on-, mid-, and off-peak periods, respectively. In addition, delivery charges apply and can be quite costly depending on the location, such as rural compared to urban areas. For example, the calculated cost of delivery charges for using 1000 kWh of energy during peak hours can $85 to $100 approximately. This is about 30 to 45 % of the total electricity bill.

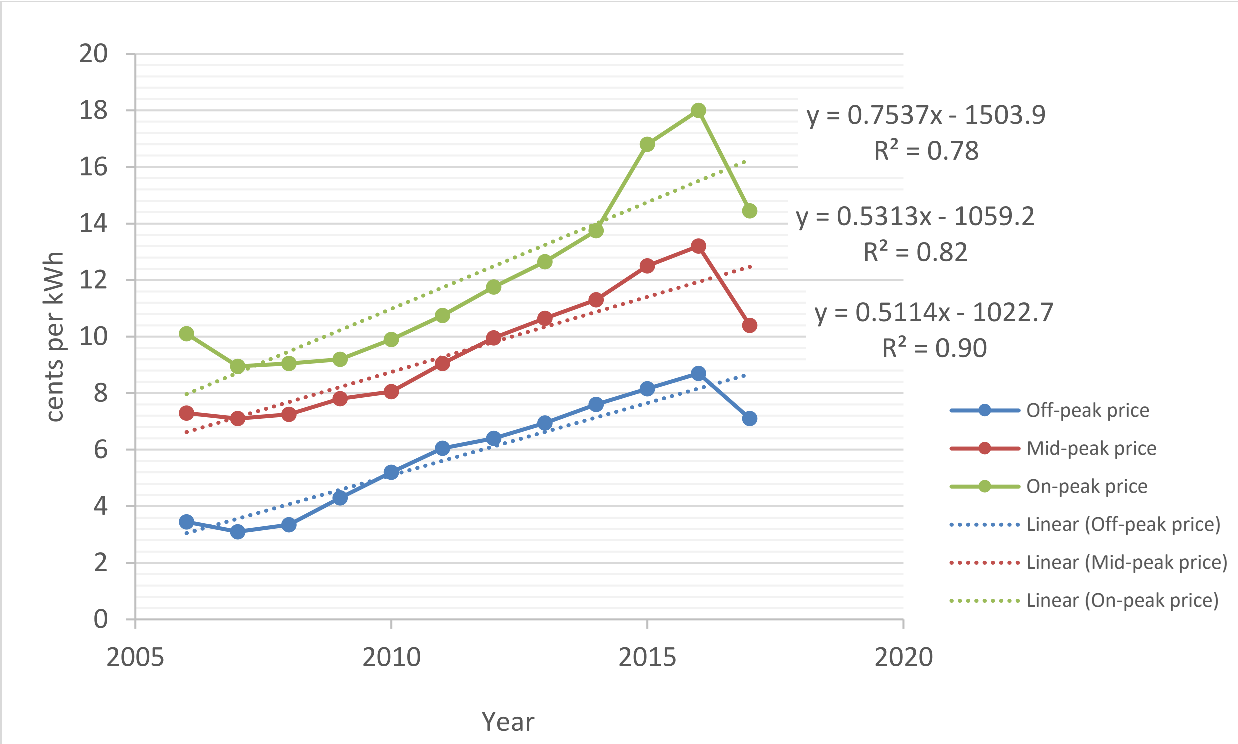

Figure 6-3: Average annual Time-of-use (TOU) rates

The increase over the last decade was due to a series of policy decisions and to shift Ontario energy production to renewable sources. The big one being the infrastructure upgrade including sustainable energy, i.e., solar and wind. Also, the signing of fixed 20-year deals with private companies to produce electricity, cancellation of two gas-fired power plants and privatizing Hydro One (Morrow and Cardoso, 2017). The increase in rates was so significant that the Ontario government had to intervene and provide some rebate to reduce the burden on consumers. However, delivery charges remain high and place a great deal of stress on rural residents, farmers, producers, washers, and processors. Sustainable energy sources such as solar and wind are very clean compared to fossil fuels with the added benefit of reducing greenhouse gases/emissions, with lower capital costs and reduced risks (Elliston et al., 2014). The push toward green and sustainable energy is great in the long run, but in the short run, the consumer will have to pay higher prices.

Due to these factors, it now costs rural consumer approximately on average of $ 260 for 1000 kWh, meanwhile this cost is about $200 or less in an urban area or within a city (Csanady and Warzecha, 2018). Rural consumers have been impacted the most, and extra precaution is needed to assess power demands for wastewater projects and what the annuals costs would be going forward given these trends. The delivery charges ranged from $28 for Toronto to $178 in Erin and even higher in some rural areas (Edwards and Nickle, 2017).

Future prices are projected to increase due to costly upgrades to electricity grid and infrastructure, refurbishing of nuclear reactors, and added cost of privatizing Hydro One. Electrical costs are hard to avoid as business usually operates during on-peak and mid-peak periods. However, some savings may be realized if the water treatment process can be delayed, such that it only operates during off-peak periods. This can easily be achieved using equalization or holding tanks, but may only be feasible for small operations. Another option is batch treatment, which may be easier for the small producer, but might not be feasible for large producers.

Power requirements for pumps, air compressors and blowers, mixing and mechanical devices consume a large portion of the overall power needed. While, monitoring, control, and dosing require a minimal amount of power for operations. Power demand and requirements can be obtained for specific equipment from suppliers and can be part of the cost analysis to increase the accuracy of cost/benefit analysis.

6.4 Solid Waste Handling Costs

Management of wash-water and wastewater from fruit and vegetable washing and processing industry using a wastewater treatment system/process will always yield solids at different stages of the treatment process. Solids can be managed through dewatering equipment, disposal to landfill, land application, settling ponds, anaerobic digestion, cattle feed to name a few. These solids may require additional treatment (dewatering) to further reduce the water content and making it easier to transport and handle. Solids can then be disposed of in garbage bins, hauled to landfill or appropriate waste management centres for final disposal. The cost of hauling waste off-site to an approved waste handling/landfill site is in the range of $70/tonne (Austin, 2013). Farmers may also land apply solid waste, such as fruit and vegetable peels or food processing waste under the NASM regulations governed by OMAFRA (OMAFRA, 2016). Due to changing regulations, this should be verified before taking any steps for implementing treatment system.

Small operations handle solids differently as compared to large operations. For example, small producers who only wash produce seasonally for a few weeks during the year have simple settling ponds to capture wash-waters and the solids contained within. The water evaporates/infiltrates leaving behind solids, which consolidate in the lower part of the pond. When required the solids can be excavated and land applied (farm, on-site) or landfilling (urban, off-site). This is possible because the small volumes of water are easier to manage as they don't require large areas/ponds. Solids handling by large producers situated in a farm setting can be in the form of land application/composting/anaerobic digestion. Otherwise, it is transported and landfilled, as the land application is not an option for facilities located in cities or urban centres. In one application of carrot washing and peeling, the peels were used as cattle feed due to its great nutritional value.

The facilities benefit by not having to pay hauling fees, as they may be partly covered by the farmers who used it for animal feed.

Anaerobic digestion of vegetable waste may be a feasible option with the provided benefit of producing heat or electricity from biogas. Anaerobic digestion and composting of solid waste from mix vegetable and carrot processing operation were investigated by Austin (2013). The results showed that mixed vegetable digestion was feasible but requires the use of a bulking agent. The results also showed that anaerobic digestion is not feasible for carrot waste by itself, due to the higher C:N ratio (Austin, 2013). However, it may be possible for a mixture of farm waste products meeting the required C:N ratio adequate for anaerobic digestion. The digestate of carrot peels from bench-scale anaerobic digestion reactor was found to have high phytotoxicity as compared to composting of solid waste (Austin, 2013). The composting process of 21 days with additional curing process allows it to be land applied.

6.5 Operator and Maintenance Costs

At times, the wastewater treatment system/train may require a dedicated operator and regular maintenance. A dedicated skilled operator in wastewater treatment operations may be required in some applications. Someone of this skill may cost approximately equivalent to the average salary of $ 65,000/year (27.7 $/hr over 52 weeks and 45-hour week work). However, it may be possible to train existing maintenance personnel, electrician, shift supervisor, and/or health and safety personnel to handle the daily operations of the wastewater treatment as some facilities do. This may be an easy task depending on the complexity of water treatment and the degree of automation/control. Training existing staff can significantly reduce the cost of hiring a dedicated person/operator for wastewater treatment.

Regular maintenance of the wastewater treatment train is necessary to avoid breakdowns and to ensure normal operations by providing the designed quality of water for end use. A maintenance schedule should be developed to understand which tasks occur hourly, daily (beginning or end of a work shift), weekly, monthly, bi-annually and annually. This will aid in determining if/when there are specific costs related to maintenance, which can be added to the economic analysis. Maintenance costs are usually presented on an annual basis, and represent 2 % of capital costs, making it easier to include in the cost/benefit analysis.

6.6 Chemical and Pumping Costs

Chemical costs can include the cost of pH adjustment using acid/base, wastewater stabilization using coagulants, and disinfection through sanitizer/cleaners when and if applicable. Chlorination and ozone may also be used to provide residual disinfection capacity to the reclaimed water in addition to ultraviolet light (UV) disinfection, as the primary disinfectant. Physicochemical treatments such as settling with coagulation and flocculation process (C&F) and dissolved air flotation (DAF) utilize coagulants to allow amalgamation of fine and dissolved particles into larger particles that will settle or float to the surface, thus increasing solids reduction efficiency. Treatments such as electrocoagulation utilize aluminum or iron electrodes to yield similar reactions as in the C&F in settling/clarification treatment. In electrocoagulation, the electrodes are consumed and require replacement based on the dissociation rate of the electrodes with the wastewater, depending on the wastewater chemistry. Adjustment of pH may be needed to optimize for treatment or for end use/application, disposal or reuse. The pH of raw wastewater or wash-water is often neutral, pH of about 7, as most fruit and vegetable washing and processing operations require potable water conditions. However, after equalization or passing of time, the pH of wash-waters may drop significantly, especially for peeling processes (pH 7 dropping to pH 4), as the organics start to break down (Mundi, 2013). As such, a base like NaOH may be used to bring the water to the neutral state.

For this study, the pH was not adjusted as the wash-water were tested soon after collection from the facility, during which period there were no significant changes in pH. During the Jar Test, all wash-waters were between 6-8 pH, hovering around neutral, as such did not require any pH adjustments. The coagulants were assessed using the Jar Test apparatus, which can show the type of coagulant and the level of dosing required to achieve a certain level of solids reduction, indicated by turbidity reduction.

The compiled study herein shows the feasibility of four different coagulants and their approximate costs: Nalco 8187 (Aluminum Chloride Hydroxide) (15.14 $/kg), Chitosan (polysaccharide from shrimp shells) (21 $/kg), Sigma-Aldrich (Poly(diallyldimethylammonium chloride)) (35.75 $/kg), and Polyglu (polymer of the amino acid glutamic acid - Water Treatment Agent PGα21Ca) (20 $/kg). It is important to note that the price may vary depending on supplier and quantity ordered. Nalco 8187 and Sigma-Aldrich coagulants are synthetic chemicals, while Chitosan and PolyGlu are naturally derived from shrimp shells and soybean, respectively. The costs for synthetic coagulants ranged from $ 15 to $36, which are quite high compared to metal coagulants, however much more effective. FeCl and Alum coagulants were explored previously on carrot washing and processing wash-waters in Mundi (2013) and the results showed the very high level of dosing was required to achieve 90% or higher reduction in turbidity. It is important to note that all coagulants are soluble in water, except Chitosan, which requires the use of acetic acid. Acetic acid is relatively inexpensive compared to the cost of Chitosan coagulant, but still an added cost.

The tested dosages for jar testing ranged from 5 to 600 mg/L for Nalco, Chitosan, Polyglu, and Sigma. For metal-based precipitation chemicals, such as Alum and FeCl, the dosages were much higher at 250 – 10,000 mg/L (Mundi, 2013). Jar testing results demonstrated that optimal dosages need to be in the range of 5 to 250 mg/L for Nalco 8187, Chitosan, PolyGlu, and Sigma-Aldrich coagulants, as shown in Table 3-8 in Chapter 3, depending on wash-water type and process. Nalco 8187 performed well for all wash-waters to other coagulants, while PolyGlu was easiest to handle, as it was in powder form. Additional chemical dosing and mixing equipment are also needed to mix coagulants and provide pH control, which can also add to capital costs. See Table C-1 in Appendix C for a detailed list of chemical costs, and properties of coagulants and pH adjustment chemicals. Coagulants were used for Settling with C&F, centrifuge, and DAF. Standalone sedimentation/settling, hydrocyclone, and screening did not use coagulants. Electrocoagulation utilize aluminum or iron electrodes, which have a rough price of 2.71 \$/kg and 0.3 \$/kg (InfoMine, 2018). The cost of which is dependent on the dissociation rate of the electrode, or rate of loss of weight in the electrode.

The cost per cubic meter of coagulant as per dosage levels are described in Table B-2. These were derived by multiplying the dosage (mg/L x 1000 mg/g x 1000 g/kg x 1000 L/m^3) by cost (\$/kg). Table B-2 can be used to derive costs for a specific volume of wash-water requiring coagulant used. To give an example, consider determining costs for a facility washing Ginseng (G1 from Table 3-8) using 200 mg/L of Nalco coagulant, with a facility flow of 100 m^3/d for 10-day operation. By using Table B-2, the cost is \$ 3.03 per $m^3$for Nalco at 200 mg/L, and cost for 100 m^3 will be 100 times greater, at \$ 303 per day. While the cost for 10-day operation will be approximately \$ 3,000.

Another example may consist of using a base (NaOH) for pH adjustment to bring the pH to neutral (pH of 7). Wash-water consisting of peels and heavy processing require a much higher dosage of NaOH as compared to just wash-waters from washing operations. This is because of the fine organics within the wash-water from processing. For this reason, Table B-3 is prepared to highlight the cost of NaOH for different dosages. For example, wash-water from peeling/cutting processes for carrot compared to the cutting of mixed vegetable use approximately 1,250 and 250 mg/L (Mundi, 2013). As such, the costs would be, 0.75 and 0.15 \$/m^3, respectively for the two NaOH dosages mentioned previously. For 10, 100, 1000 m^3, flows the costs can range from \$ 1.5 – 7.5, \$ 15 – 75, \$ 150 – 750, respectively, for the two, high and low NaOH dosages.

Chemical costs can vary depending on the level of coagulant optimization, the variablility of wash-water quality during the day-to-day operations, which can change based on product and origin of the product (soil types/amount of soils attached to root vegetables). Thus, it is important to consider all aspects of the operation and treatment objectives to reduce chemical costs. Reducing wash-water volume will have a proportional reduction in chemical/coagulant used. Thus, it is very important to reduce water consumption first as much as possible, before implementing treatment options.

Using the optimized dosages, as listed in Table 3-1 in Chapter 3, Table 6-1 was created to show the cost of implementing optimal coagulants based on available facility flows. Daily and annual flow rates as provided in Table A-1 in Appendix A1 were used to calculate the costs for each facility as listed in Table 6-1. The costs range from couple hundred dollars a year for very low flow/volume to hundreds of thousands of dollars a year for very large facilities. Facility C2 in Table 6-1 stands out as the costs are highlighted to be between \$ 41,000 to \$ 165,000. The higher cost of \$ 165,000 (higher coagulant dosage) represent the worse conditions (excessive loading of solids) for wash-waters, that may only exist partly during the operation cycle, in addition to the very high flows.

Table 6-1: Approximate coagulant costs for studied facilitates if implementing C&F or DAF

Facility	Process Type	Optimized Coagulants - Type (See below) and Dosage (mg/L) **	Coagulant Cost per $/m3 of corresponding dosage (Table 6-1)	Flow (m^3/hr)	Annual Flow (m^3/year)	Cost Range ($/year)
A2	WP	N-200	3.03	10	20,800	63,024
		C-50	1.05			21,840
C2	WP	N-25 to N-100	0.38 - 1.51	114	109,440	41,587 - 165,254
G1	W	N-200	3.03	15	750	2,273
		P-25	0.5			375
G2	W	C-150	3.15	1.4	180	567
LG1	W	N-10	0.15	5*	2,080*	312
MV1	WP	N-25 to N-50	0.38 - 0.76	15	14,400	5,472 - 10,944
		P-200	4			57,600
P1	W	N-50 to N-200	0.76 - 3.03	1.7	1,088	826 - 3,296
P2	W	N-150 to N-250	2.27 - 3.79	2.8	1,792	4,067 - 6,791
		C-25	0.53			950
P3	WP	C-25 to C-150	0.53 - 3.15	5*	3,200*	1,696 - 10,080
SP1	W	N-5 to N-200	0.08 - 3.03	0.1	10	1 - 31.0
SP2	W	N-25	0.38	5*	480*	182

**Coagulant Legend:
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 - $FeCl_3 \cdot 6H_2O$
1,2 Corresponding dosages

*Missing flow were substituted with 5 m^3/hr and the operation time was taken from similar facilities.

It is evident that flow/volume play a vital role in reducing costs of chemicals. One simple way to reduce costs for coagulants is to allow the wash-water to settle under the influence of gravity, in a settling tank or a clarifier to reduce solids, or using gravity screening. Effective settling is only possible with low flow/volume as multiple settling/aeration ponds can be used to reduce solids as much as possible, as in the example of P2 facility (See Table 3-1 in Chapter 3). Also, in the case of the G2 where the wash-water stream was heavily concentrated due to very low flows, 1.4 m^3/h. Even though the dosages are high for G, due to the low flow/volume the cost of coagulant used can be reduced significantly. However, large facilities require the greater area to accommodate the large volumes, which are very land intensive and costly. Slow flow rates or small volumes are more viable as they take up less land.

Pumping costs for conveying water and wastewater also needed to be considered. Three pumps were considered as examples to demonstrate the cost per cubic meter of pumped/treated waters. These were based on a flow rate of 180, 15 and 3 m^3/hr, as highlighted in Table 6-1. The capital costs for the pumps can range from $500 to $10,000, while the dollar cost per cubic meter of water pumped/treated can range from $0.011 to $0.017. Pumps with low efficiency can have higher electricity costs as seen for 3 m^3/hr flow, an example in Table B-4, while pumps with higher efficiency and flow throughput can cost the same. There is a balance between selecting the right flow and efficiency, which is based on the required head pressure. The costs of associated pumping can be used in estimating total operating costs.

In general, chemical costs can be one of the highest operating costs for physiochemical wastewater treatments. The selection of coagulant used for treatment can also have a significant impact on the cost, such as polymer-based coagulant compared to a natural or metal based. While metal based coagulants, such as Alum have been used extensively in the water/wastewater treatment industry, they are still not as effective as polymer-based coagulants, such as Nalco 8187.

6.7 Capital Costs

In addition to operating costs such as chemical costs, capital costs are significant. Wastewater treatment equipment such as screening, hydrocyclones, settling/clarification, mixing tanks for

C&F, chemical dosing, DAF, centrifuge, and electrocoagulation are customized for certain application or are based on flow/volume throughput. See Appendix E.2 and E.3 for a typical equipment types and brief list of companies which provided some rough costs. Information is also available through OMAFRA's newly published *Vegetable and Fruit Washwater Treatment Manual – Publication 854* (OMAFRA, 2018). This manual also highlights testing of applicable treatment technology such as screening, hydrocyclone, and various filtration technologies.

Capital costs require obtaining pricing from different equipment suppliers, as treatment trains require many different types of pipes, fittings, equipment, controls, valves, etc. As such, it is very difficult to estimate accurate costs for every scenario of treatment, size, and application. Equipment manufactured locally/nationally maybe expensive relative to importing it from China/India. Some differences may exist in equipment quality, such as the quality of steel. However, quality equipment is always available from overseas, i.e., Germany, if one is willing to pay for it. It is recommended to use local suppliers that provide support to help size and cost the equipment before final purchase.

To provide rough cost estimates, capital costs of various equipment and treatments were obtained from HOMES Water, H2O Flow and Vector Process Equipment. Due to the difficulty of providing an accurate estimate, it is always recommended to consult directly with the manufacturer/supplier/engineering consulting firm about costs. However, HOMES Water provided up to date cost estimates, while the costs estimated from H2O Flow and Vector Process Equipment were from 2013, but were updated using Engineering News-Record Construction Cost

Index (ENRCCI) (Petrisca, D. – HOMES Water, personal communication, March 14, 2018). The cost of existing and implemented full-scale treatments are listed for available facilities.

Table 6-2 provides a list of treatment equipment and its corresponding costs including costs of currently implemented solutions. The three different types of screening equipment listed include Amiad Filters, Rotating Screen, and Gravity Flow. These provide the screening necessary to reduce the solids loading in wastewater and to remove large foreign material and girt. The cost of these range from \$ 20,000 to \$ 125,000 depending on equipment flow capacity, automation control and back-wash systems. Screening using mesh/amiad filters can be very difficult to select, especially with high solids content wash-waters/wastewaters, as they are prone to clogging. Settling and settling with C&F can range from \$ 40,000 to \$ 75,000. The increased cost for C&F is due to dosing and mixing equipment that is necessary to properly mix the coagulants. Which still doesn't include the operating chemical costs of coagulant and chemicals. Recent advances in plate settlers allow improved reduction in solids, in addition to handing higher flows under a small foot-print. This is due to the increased area provided by the multiple plates within the settler.

Centrifuge treatment ranges from \$ 180,000 to \$ 220,000 depending on flow capacity, which is quite high for a single piece of equipment. However, it is important to note that the centrifuge may also serve as a dewatering equipment for other treatments, in the same treatment train. Electrocoagulation is moderately priced at about \$ 50,000 and may be a feasible technology alternative to C&F, as it eliminates dosing equipment and chemical mixers/mixing zones, as well the coagulants, which can be very expensive as highlighted in Table 6-2.

DAF units can be effective at handling dissolved solids and work well for solids with a specific gravity of close to water (SG = 1) or above, as they are easier to float. DAF units cost $ 95,000 without dewatering to $ 170,000 with dewatering equipment (centrifuge). Biological treatment consisting of four-stages including settling, aeration, nutrient removal, and final settling implemented at P1 cost roughly about $ 250,000. The costs were especially high due to use of concrete cells rather than settling ponds or ground basins, with a volume of 100 m^3 per cell.

Membrane bioreactor combine biological treatment with filtration in one step, making it very effective to treat wastewater, however, at the same time making it complicated and expensive. MBR combined with reverse osmosis (RO) and Ultra Violet (UV) disinfection can form a complete system, as in the case of A1 facility. Due to the complexities involved in the MBR systems costs can range from $ 500,000 to $ 700,000 (A1 Facility; Moore, 2014). Membrane filtration systems alone cost a lot, as noted in Table 6-2, where ultra-filtration systems with sludge thickener can be in the range of $ 200,000 to $ 250,000. Ultra-filtration can only be used after majority of suspended solids have been reduced through primary treatment by using settling, settling with C&F, DAF, etc. UV disinfection can be implemented to disinfect the recycled water before it used in the process or other reuse applications. In addition, holding tanks can also cost anywhere from $ 8,000 to $ 18,000 from 5 to 15 m^3 PVC tanks, which may be needed for holding the treated wash-waters.

The capital cost of each treatment equipment was converted to cost per cubic meter of water treated ($\$/m^3$) for ease of comparison and to provide an approximate estimate. This was done in three steps, first the interest and amortization period was selected, second the capital recovery factor and annual debt service was calculated, and finally, the annual debt service was normalized to different flows to obtain the cost per cubic meter of water treated. The interest rate and amortization period for wastewater treatment capital loans are typically 8 % and 20 years, respectively (Asano et al., 2007). The annual debt service is the amount required to be paid back each year towards the loan and accumulated interest. The cost of borrowing money can be significant as highlighted by the 8 % interest rate, however, may be the only option to finance the wash-water/wastewater treatment and reuse system. See Cost Appendix for sample calculations. Table 6-3, highlights the calculated cost per cubic meter of water treated for each type of treatment/equipment for different annual volumes.

Table 6-2: Approximate costs for observed and suggested full-scale treatments

Treatment Technology	Approximate Cost (CDN $)	Facility Type/Flow	Type (Cost Source/Facility implemented)
Screening (100-200 um)	40, 000	N/A	Amiad Filters with one filter - no standby (HOMES Water)
Screening	125,000	15 m^3/hr	Dual Rotating Screen (C1 Facility)
Screening	20,000	1.7 m^3/hr	Gravity flow filter (P1)
Settling	20,000 – 40,000*	N/A	Simple plate coalescing filter, and tanks (HOMES Water)
Settling with C&F	50,000 – 75,000*	N/A	With polymer makeup and coagulation dosing skids (HOMES Water)
Centrifuge Solid liquid Separation	220,000	15-30 m^3/hr	(Vector Process Equipment)
Centrifuge Solid liquid Separation	180,000	15 m^3/hr	Flottweg – fully automated
Electrocoagulation	50,000	5.7 m^3/hr	Powell – EC system, tank and electrodes (HOMES Water)
Dissolved Air Flotation No dewatering equipment	95,000	6.8 m^3/hr	(HOMES Water)
Dissolved Air Flotation with centrifuge for dewatering sludge	170,000	16 m^3/hr	(H2O Flow)
Biological Treatment	250,000	1.7 m^3/hr	4 stages – settling, aeration, nutrient removal, settling (P1)
Membrane Bioreactor (MBR) with filtration, Reverse Osmosis filtration, and UV Disinfection	500,000	10 m^3/hr	Apple - Washing and berry processing, juice plant (A1)
Small Scale Ultra Filtration	10,000	2 m^3/hr	(Alibaba Website)
Membrane Filtration	200,000 – 250,000*	N/A	Ultra-filtration with thickener (HOMES Water)
Disinfection	10,000 30,000	2.7 m^3/hr 14 m^3/hr	UV Disinfection unit with a quartz tube and self-cleaning (Alibaba Website)
Holding Tanks	8,000 15,000 18,000	5 m^3 10 m^3 15 m^3	PVC Tank – Cylindrical (HOMES Water)
*Higher Price used as a conservative measure to calculate the cost per cubic meter Note: Prices vary from one supplier/manufacturer to another. Low-cost solutions are always available, but require time and effort to look for suppliers within and outside the province of Ontario. The USA can also be used to source equipment, due to their increased selection and supplier lists. The option of importing from India/China may also exist, however, require great care to ensure the value is equivalent to the cost.			

The costs have been ranked from highest cost to lowest cost. The following discussion relates to costs of the annual flow of 100,000 m^3. It is evident that membrane bioreactors treatment systems, as expected would be costly at \$0.51 per m^3, however, they offer the chance to produce potable water quality standards. Followed by biological treatments and membrane filtration units at a cost of \$0.25 per m^3, this makes sense as biological treatment require aeration and nutrient removal mediums, and filtration materials and units are advanced filters. Centrifuge, DAF, Screening, Settling with C&F, electrocoagulation, and screening follow next with costs ranging from \$0.22 to \$0.04 per m^3. Screening costs can vary significantly, as there are many different types. Disinfection, gravity screening, and storage can cost from \$0.03 to \$0.01 per m^3. The costs highlighted in Table 6-3 can be summed depending on the type of treatment units used in the treatment train and can provide a rough estimate of implementation costs. One can also use the methods used in this chapter to derive more detailed analysis and/or specific to facility conditions.

Table 6-3: Cost of Treatments in $/m^3$ of treated waters

			Volume per operation period (m^3/year)					
Equipment[1]	**Cost ($)**	**Annual debt service[2] ($)**	**100,000**	**10,000**	**1,000**	**100**	**10**	**Rank**
Membrane Bioreactor (MBR) with filtration, Reverse Osmosis filtration, and UV Disinfection	500,000	50,926	0.51	5.09	50.93	509	5,093	1
Biological Treatment	250,000	25,463	0.25	2.55	25.46	255	2,546	2
Membrane Filtration	250,000	25,463	0.25	2.55	25.46	255	2,546	2
Centrifuge (Solid liquid Separation)	220,000	22,407	0.22	2.24	22.41	224	2,241	4
Centrifuge (Solid liquid Separation)	180,000	18,333	0.18	1.83	18.33	183	1,833	5
Dissolved Air Flotation with centrifuge for dewatering sludge	170,000	17,315	0.17	1.73	17.31	173	1,731	6
Screening - Rotary	125,000	12,732	0.13	1.27	12.73	127	1,273	7
Dissolved Air Flotation (No dewatering equipment)	95,000	9,676	0.10	0.97	9.68	97	968	8
Settling with C&F	75,000	7,639	0.08	0.76	7.64	76	764	9
Electrocoagulation	50,000	5,093	0.05	0.51	5.09	51	509	10
Screening (100-200 um) – Amiad Filters	40,000	4,074	0.04	0.41	4.07	41	407	11
Settling	40,000	4,074	0.04	0.41	4.07	41	407	11
Disinfection – 14 m^3/h	30,000	3,056	0.03	0.31	3.06	31	306	13
Screening – Gravity	20,000	2,037	0.02	0.20	2.04	20	204	14
Holding Tanks – 15m^3	18,000	1,833	0.02	0.18	1.83	18	183	15
Holding Tanks – 10m^3	15,000	1,528	0.02	0.15	1.53	15	153	16
Small Scale Ultra Filtration	10,000	1,019	0.01	0.10	1.02	10	102	17
Disinfection – 2.7 m^3/h	10,000	1,019	0.01	0.10	1.02	10	102	17
Holding Tanks – 5m^3	8,000	815	0.01	0.08	0.81	8	81	19

[1]Match with corresponding size/flow capacity listed in Table 6-1, when selecting treatment for costing.
[2]Interest rate of 8 % and an amortization period of 20 years was used (Asano et al., 2007).
Disclaimer: The prices/costs mentioned highlight approximate values as suppliers only provide exact cost for particular wash-water treatment train and application specified by the customer.

A typical treatment train will consist of preliminary (screening), primary (solids reduction – and hydrocyclone and settling/clarification), secondary (BOD reduction – Settling with C&F, DAF, and Electrocoagulation), and tertiary (pathogen elimination – UV disinfection) treatment. Depending on the application/end use water quality requirement, some steps noted above may be avoided. This is in line with what was observed during the study period at different facilities using treatment systems, as some facilities didn't use secondary or tertiary treatments since they were able to blend the treated water with clean water to reduce contamination or to meet standards. As stated in the *Fresh fruit and vegetable Regulations*, Minister of Justice (2012) that, "the final rinse water, if reused, is used only in the initial washing or fluming of the produce; and" and "only potable water is used in the final rinsing of the produce to remove any surface contaminant before packing;", the use of water reuse is already allowed.

Using the concepts of a typical wastewater treatment components, as mentioned above, the following treatment train was put together to provide an example of a system allowing for complete reuse of the wastewater or wash-water from fruit and vegetable washing and processing at a flow rate of approximately 114 m^3/hr: (1) preliminary treatment consisting of screening, (2) primary treatment consisting of DAF utilizing coagulants with dewatering equipment, (3) tertiary treatment consisting of membrane filtration and high flow UV Disinfection. While a second simpler treatment train for smaller flows and lower solids levels may consist of: (1) screening (2) electrocoagulation (3) small-scale ultrafiltration unit (4) low flow UV disinfection. The two options are outlined below in Table 6-4.

The costs in $/m^3 of treated water were obtained in a similar method as highlighted in Table 6-4. The total capital costs sum up to $ 0.58 and 0.12 per m^3, respectively for Option One and Option Two. While surprising a coincident, the operating costs were for both option were the same at $1.62 per m^3. This was since the annual maintenance for the cheaper system was quite a bit. The total capital, operating, and maintenance costs were $2.20 and $1.74 per m^3, respectively for Option One and Option Two. This would be the cost that would be compared to the cost of water/wastewater services to determine if the treatment/reuse options are feasible. Compared to the Region of Peel water/wastewater rates, Option One cost is about $0.11 lower, while Option Two is $0.57 lower. Based on the magnitude of these differences, a facility may choose to implement a treatment.

The benefits associated with water reuse can lead to a reduction in freshwater used as process water, thus reducing the cost to obtain this precious input resource. Not to mention, the minimization of any surcharges previously arising from BOD and TSS overloading to the municipal wastewater treatment system or discharge. The cost of water for the Region of Peel is at 2.31 $/m^3, while Guelph and Waterloo are much higher. This rate is for Region of Peel for the year 2018, although it is expected that the rate will increase significantly over the next 20 years to about 3.89 $/m^3 (derived previously) for the year 2038.

Table 6-4: Estimate of Capital and operating costs for the two example treatment options

Cost Type	Parameters	**Option 1 – High flow high solids**	**Option 2 – Low flow low solids**	**units**
	Flow	114	2.8	m^3/hr
	Annual Volume	109,440	1,792	m^3
		-	-	
Capital	Screening	0.14	0.02	$/m^3$
	DAF (with a centrifuge for dewatering sludge)	0.16	-	
	Electrocoagulation	-	0.05	
	Settling	-	0.02	
	Membrane Filtration	0.23	-	
	Small Ultra Filtration Unit	-	0.01	
	UV Disinfection	0.03	0.01	
	Holding Tank	0.02	0.01	
Total Capital		**0.58**	**0.12**	
	Chemical Dosage	Nalco 100 mg/L	Chitosan 25 mg/L	
Total Chemical	Chemical Cost	1.51	0.53	$/m^3$
Total Maintenance	Annual (2% Assumed)	0.11	1.09	
Total Operating and maintenance costs		**1.62**	**1.62**	
Total (Capital + Operating and Maintenance) Costs		**2.20**	**1.74**	

Savings for rural producers/farmers are hard to quantify as they are in the form of reducing risk, which cannot be easily quantified monetarily. Some scenarios for rural producers is the lack of fresh water arising from drought or via pressure from communities to reduce water uptake, requiring additional water to be trucked in or bulk water delivery. As mentioned previously, this can be as high as 10 $/m^3 in some cases, compared to treatment Option One and Two, at $2.20 and $1.74 per m^3, respectively. This especially applies to facilities not part of a farm, as farms use large amounts of water for agricultural activities, depending on the capacity of their well, as such the costs can be minimal compared to water/wastewater services from the municipality. Another scenario, is that of wash-water management, by implementing water reuse, the cycle is closed, and the risk of polluting the nearest stream, river, or lake is greatly reduced. Unexpected and costly operation shutdown may be possible by MOECC if operations are polluting the environment, where the risk of loss of business and money is tremendous. The biggest risk of all is the contamination of source waters, which can occur from agricultural, industrial, and flooding/drought activities.

Regardless of the feasible options and/or the best practices utilized for wash-water and solids management, it is important to know the regulations surrounding wastewater effluent requirements and solid waste management handling. This will help in making cost-effective decisions. Another scenario is that of putting in a sustainable operation in place, which can allow the facility to increase production without having to worry about the increases in wash-water volumes impacting external factors. Sustainability has been highlighted by some companies in the form of having sustainable technologies to run their operations. Such examples include, but not limited to, solar energy usage, water recycling systems, and waste reducing methods, all of which have been implemented at Facility A1.

The capital and operating costs/trends derived in this document were summarized in an easy to use Microsoft Excel worksheet with simple input/output interface. The detailed costs estimates exist in the background while the user interface provides an easy way to see the calculated results based on flow and selected treatment. The worksheet was further enhanced by the use of multiple linear regression (MLR) and artificial neural network (ANN) predictive models for treatment selection. The combination of the costing and treatment predictive models into one easy to use worksheet provides stakeholders with a tool for making the decision on wash-water treatments. Some drawbacks exist, such as the high variability of wash-water samples and treatments studied, leading to variability in the developed models and the conservative costings estimates. The models still provide a valid method which can be improved by using larger datasets. The developed toolkit worksheet was not previously available to stakeholders and furthers the research in the field of wash-water and wastewater treatment of fresh-cut pre-prepared, minimal processing and washing of fruit and vegetable sector.

The cost/benefit or economic analysis shows different costs involved in setting up and running a wastewater treatment system. Extensive problem definition is needed, so the goal or the objective of the treatment is clear, whether the wash-water is disposed of or is recycled in the process. Along with having an aligning strategy for solids management. The overview highlighted in this section serve for estimating costs.

Chapter 7: Conclusions and Recommendations

7.1 Conclusions

The completion of the study added new knowledge to the field of wastewater treatment, more specifically, how to treat the wash-water generated by the minimally processed, fresh-cut fruit and vegetable sector. This included the characterization of the wash-water, evaluation of various technologies which included reuse options. The bench-scale and full scale testing and assessment findings are vital for farmers, producers, washers, processors, researchers, consultants and professional engineers. The findings can be summarized as follows:

- Characterization of wash-water and wastewater from fruit and vegetable washing and processing industry have been highlighted in terms of water quality. Water quality parameters for some wash-water did not previously exist. It was evident that the wash-waters studied showed highly variable water quality parameters, which was due to a number of key factors. These factors include mechanical removal of soils for root vegetable before washing, flows/volumes used for continuous and batch washing/processing, type of process (washing versus washing including processing (cutting, budding, and/or peeling) and operator awareness of water/wastewater impact.
- Assessed on-site treatments and their effectiveness for reducing typical water quality parameters, such as TS, TDS, TSS, TP, TN, COD, BOD, and other measured water quality parameters were dependent on raw wash-water quality, treatment effectiveness – based on design and proper treatment operations, such as controlled flow into settling tank. Previous studies only considered single treatments, while this study studied many implemented treatments, covering a variety of wash-water types.

- Developed novel treatment decision matrices (treatment tables) from bench-scale testing and analysis to provide an estimate of treatment efficiency, based on wash-water (product), process, and treatment type. Previous studies have not evaluated wash-water over many treatments to see the effect. The treatment effectiveness was converted to letter grades such as E, for excellent reduction efficiently (>90%) for ease of use.
- Analyzed additional datasets provided by OMAFRA and performed a combined/meta-analysis on all characterization data, including data collected during Ph.D. work. Developed the Power-Rank tool for assessing risk from different wash-waters in terms of the average and standard deviation of various water quality parameters. The water quality parameters were converted to ranks (worst to best or 0 – 1), which were utilized to develop the Power-Rank equations. For example, predicting TSS of raw wash-waters can be done by $TSS_{Average} = 35(x)^{-1.87}$ using any of the provided ranks corresponding to different fruits or vegetable products/operation type.
- Developed novel models and tools for wash-water treatment prediction and feasibility of the effective technologies. The analysis of decision matrices and the additional data used for Power-Rank modes was extended to formulate mathematical models utilizing MLR and ANN techniques. MLR produced linear equations that can easily be defined making it practical for use, while the ANN equations are defined by equations involving tanh functions, as stated in Chapter 5. These were simplified with the use of an Excel worksheet.
- Developed cost/benefit analysis methods to highlighting the selection of the treatment based on operating and capital costs, facility operational parameters, and benefits from water reuse. This was added to the Excel worksheet to complement treatment selection tool with cost/analysis.

7.2 Recommendation

The research study was successful in achieving its proposed objectives to provide a greater understanding and to generate tools for predicting effluent water quality of the wash-water treatment studied herein. The study filled its proposed objectives and deliverables as part of the requirement of this doctoral program. Because of the project timeline and practical limitations, some outstanding issues remain that should be improved on in the future. The following recommendation includes:

- Due to the large number of treatments and wash-waters studied, there remains a challenge to ensure enough representative samples are collected. As such, continuous improvement of the prediction tools may be necessary to refine results.
- While the wash-water can be treated, solids management still presents a challenge, except for centrifuge, which can handle both. As such the application of conventional mechanical dewatering techniques for wash-water solids management should be studied. In addition to research on the use of solids as by-products for the animal, human or other industrial uses.
- This study was successful in building a universal model for all wash-waters, however, the large variability in wash-waters samples translated into the models as well. Further research should consider narrowing the scope to reduce variability or collect very large datasets to include each type of wash-water and treatment studied.
- Detailed full- or pilot-scale testing involving rapid measurement should be considered to further refine the developed models and to innovate the models for use with continuous systems to optimize operations. Such as the use of the product, process, and turbidity

measurement correlated with other water quality parameters, such as TSS, TP, TN, COD, BOD may be used for optimizing and reducing coagulant costs.

Chapter 8: References

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Appendix

Appendix A. Supporting Charts and Figures

Appendix A1 Flow Charts

Table A-1: Flow information of different facilities in the Fruit and Vegetable Washing and Processing industry per hour and annum, ranked from highest to lowest

Product/Facility Type	Flow (m3/hr)	Operation Length per year	Volume per operation period (m3/year)	Category Type*
Carrot	**114**	**120 days/8 hr-day**	**109,440**	**RV**
Apple	10	All year/8 hr-day	20,800	TF
Mixed Vegetable	15	N/A	14,400	RV
Carrot	14	120 days/8 hr-day	13,440	RV
Carrot	12	65 days/8 hr-day	6,240	RV
Apple	1	Year around	2,080	TF
Potato			1,987	RV
Potato	**2.8**	**80 days/8 hr-day**	**1,792**	**RV**
Potato	1.7	80 days/8 hr-day	1,088	RV
Mushroom			1,040	AG
Mushroom			780	AG
Ginseng	15	5 days/10 hr-day	750	RV
Zucchini			632	AG
Tomatoes			413	AG
Tomatoes			369	AG
Ginseng Seed			313	RV
Snap Beans			300	AG
Melons			188	AG
Ginseng	2	10 days/9 hr-day	180	RV
Peppers			95	AG
Peppers			38	AG
Tomatoes			27	AG
Boston Lettuce			18	LG
Sweet Potato	0.1	12 days/8 hr-day	10	RV
Squash/Sweet Potato			8	RV
*RV – Root-vegetable, LG – Leafy Greens, AG – Above Ground, and TF – Tree Fruit				

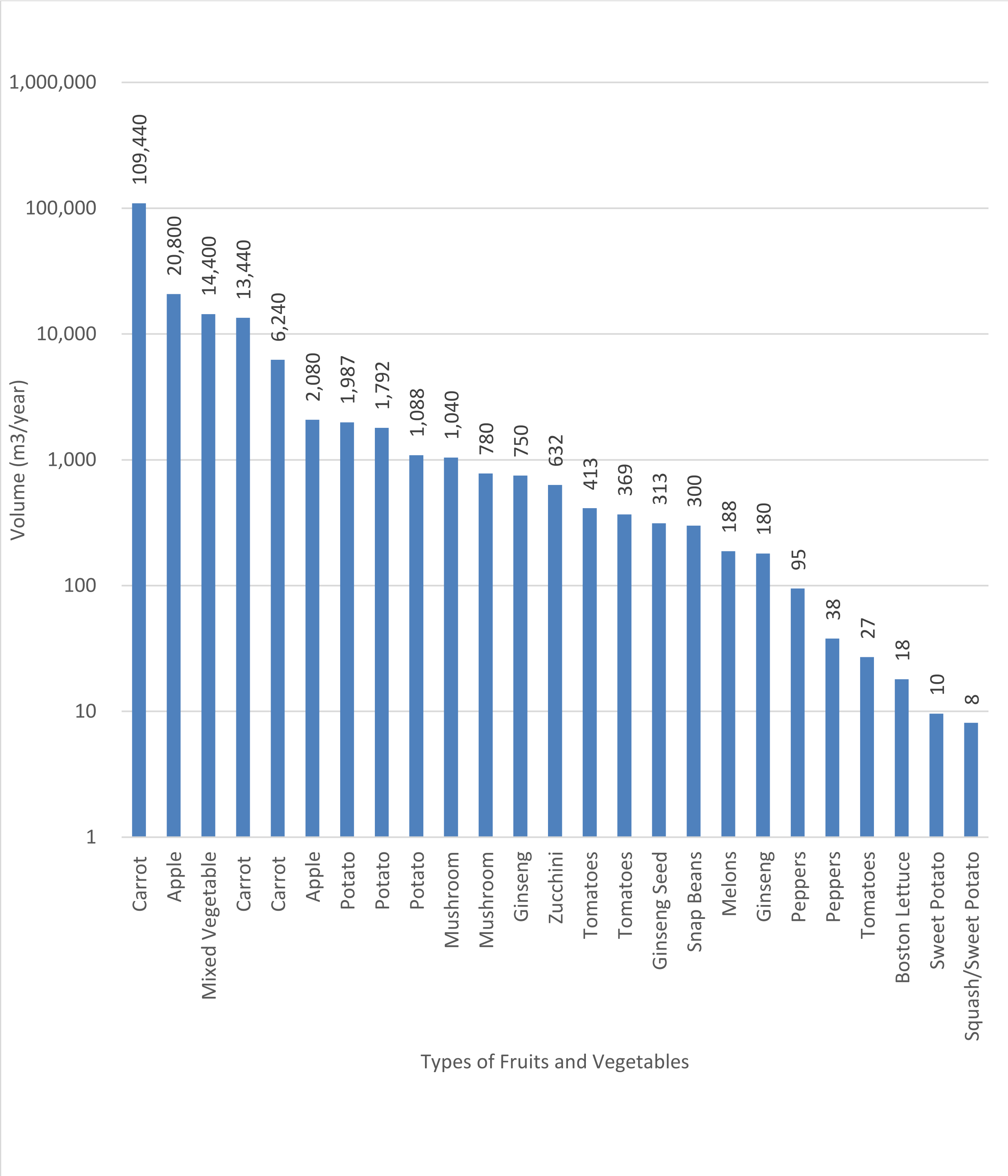

Figure A-1: Annual volume generated by different facilities in (m^3/year)

Table A-2: Water use per Product Category

Category of Product and Facility/Product	Average of Volume per operation period (m3/year)
Above Ground (AG)	
Melons	188
Mushroom	910
Peppers	67
Snap Beans	300
Tomatoes	269
Zucchini	632
AG Total	**388**
Leafy Greens (LG)	
Boston Lettuce	18
LG Total	**18**
Root Vegetable (RV)	
Carrot	43,040
Ginseng	465
Mixed Vegetable	14,400
Potato	1,026
Squash/Sweet Potato	8
Sweet Potato	10
RV Total	**13,413**
Tree Fruit (TF)	
Apple	5,840
TF Total	**5,840**

Appendix B. Cost and Economic Analysis

Table B-1: Time-of-use (TOU) rates

	(¢ per kWh)		
Year	**Off-peak price**	**Mid-peak price**	**On-peak price**
2017	7.1	10.4	14.45
2016	8.7	13.2	18
2015	8.15	12.5	16.8
2014	7.6	11.3	13.75
2013	6.95	10.65	12.65
2012	6.4	9.95	11.75
2011	6.05	9.05	10.75
2010	5.2	8.05	9.9
2009	4.3	7.8	9.2
2008	3.35	7.25	9.05
2007	3.1	7.1	8.95
2006	3.45	7.3	10.1

Table B-2: The cost of coagulant per cubic meter based on dosage level

Cost ($/kg)	15.14	35.75	21.00	20.00
Coagulants	Nalco (N)	Sigma (S)	Chitosan (C)	PolyGlu (P)
Dosage (mg/L)	$/m^3			
1	0.02	0.04	0.02	0.02
5	0.08	0.18	0.11	0.10
10	0.15	0.36	0.21	0.20
25	0.38	0.89	0.53	0.50
50	0.76	1.79	1.05	1.00
100	1.51	3.58	2.10	2.00
150	2.27	5.36	3.15	3.00
200	3.03	7.15	4.20	4.00
250	3.79	8.94	5.25	5.00
300	4.54	10.73	6.30	6.00
350	5.30	12.51	7.35	7.00
400	6.06	14.30	8.40	8.00

Table B-3: Cost of NaOH for neutralizing the wash-water

NaOH Cost ($/kg)	0.6
Dosage (mg/L)	$/m3
100	0.06
250	0.15
500	0.30
750	0.45
1000	0.60
1250	0.75
1500	0.90

Table B-3: Pumping Costs

Max Flow (m3/hr)	Head (m)	Efficiency (%)	Cost ($)	Cost ($/hr)	Cost ($/$m^3$)
180	20	70	10,000	2.00	0.011
15	15	69	1000	0.12	0.008
3	16	34	500	0.04	0.017

Pumping Costs

Example 1: For the worked example, having a flow of 180 m^3/h, head of 20 m, the total assumed efficiency of 0.70, an electricity rate of 14.45 ¢ per kWh, the power demand of 18.5 kWh, and at a cost of about $ 10,000 (Alibaba).

Convert from SI to Imperial units before using the formula below.

Currency conversion rate on April 3, 2018 ➔ 1 CDN = 0.78 USD

$$\text{Cost of pumping} = \frac{0.746 \times \text{Flow [GPM]} \times \text{Head [Feet]} \times \text{Electricity Rate [USD/kWh]}}{3960 \times \text{Efficiency Pump and Motor [\%]}}$$

$$= \frac{0.746 \times 793 \times 66 \times 0.11}{3960 \times 0.70}$$

Cost per hour = 1.55 USD/hr ➔ 2.00 CDN/hr

Cost per m^3 = Cost per hour / pump flow capacity

$$= (\$2/\text{hr})/(180\text{m}^3)$$

$$= \$\ 0.011/\text{m}^3$$

Therefore, it will cost \$ 2.00 per hour to run this pump or \$ 0.01/m^3 of treated waters.

Example 2: For the worked example, having a flow of 15 m^3/h, head of 15 m, the total efficiency of 0.69, an electricity rate of 14.45 ¢ per kWh, the power demand of 1.5 kWh, and at a cost of about \$ 1000 (Alibaba).

Convert from SI to Imperial units before using the formula below.

Currency conversion rate on April 3, 2018 ➔ 1 CDN = 0.78 USD

$$\text{Cost of pumping} = \frac{0.746 \times \text{Flow [GPM]} \times \text{Head [Feet]} \times \text{Electricity Rate [USD/kWh]}}{3960 \times \text{Efficiency Pump and Motor [\%]}}$$

$$= \frac{0.746 \times 66 \times 49 \times 0.11}{3960 \times 0.69}$$

Cost per hour = 0.097 USD/hr ➔ 0.12 CDN/hr

Cost per m^3 = Cost per hour / pump flow capacity

$$= (\$0.12/\text{hr})/(15\text{m}^3)$$

$$= \$\ 0.008/\text{m}^3$$

Therefore, it will cost \$ 0.12 per hour to run this pump or \$ 0.01/m^3 of treated waters.

Example 3: For the worked example, having a flow of 3 m^3/h, head of 16 m, the total efficiency of 0.34, an electricity rate of 14.45 ¢ per kWh, the power demand of 0.55 kWh, and at a cost of \$ 500 (Alibaba).

Convert from SI to Imperial units before using the formula below.

Currency conversion rate on April 3, 2018 ➔ 1 CDN = 0.78 USD

$$\text{Cost of pumping} = \frac{0.746 \times \text{Flow [GPM]} \times \text{Head [Feet]} \times \text{Electricity Rate [USD/kWh]}}{3960 \times \text{Efficiency Pump and Motor [\%]}}$$

$$= \frac{0.746 \times 12 \times 52 \times 0.11}{3960 \times 0.34}$$

Cost per hour = 0.038 USD/hr ➔ 0.049 CDN/hr

Cost per m^3 = Cost per hour / pump flow capacity

= ($0.05/hr)/($3m^3$)

= $ 0.017/m^3

Therefore, it will cost $ 0.05 per hour to run this pump or $ 0.02/m^3 of treated waters.

<u>Capital cost of treatments converted to cost per cubic meter</u>

Interest rate = 0.08 or 8 %

Amortization period = 20 years

Loan principal = cost of treatment = i.e., $ 500,000 (Capital Cost of MBR)

<u>Calculate the capital recovery factor (A/P) for 20 years at 8 percent interest.</u>

$$\text{Capital recovery factor} = \frac{i(1+i)^n}{(1+i)^n - 1}$$

$$= \frac{(0.08)(1+0.08)^{\wedge 20}}{(1+0.08)^{\wedge 20} - 1}$$

$$= 0.101852$$

<u>Calculate annual debt service</u>

Annual debt service = loan principal x capital recover factor

= $ 500,000 x 0.101852

= $ 50,926 per year for 20 years

Cumulative debt service = Annual debt service x amortization period

= $ 50,926 x 20 years

= $ 1,018,520

Therefore, it will cost $ 51,000 a year to loan money to buy an equipment.

Calculate the cost per cubic meter of treated water based on annual volume of 100,000 m^3

Cost per cubic meter = annual debt service / annual volume

= (\$ 50,926) / (100,000 m^3)

= \$ 0.51 per m^3 of treated waters

Therefore, it will cost approximately \$ 0.51/m^3 to treat waters using an MBR system with an annual volume of 100,000 m^3.

Appendix C. Chemicals Used and Calculations

Appendix C1 Chemical (Coagulant) costs and properties

Table C1-1: Solution Concentrations

#	Name/Chemical Formula	Molar Mass (g/mole)	Product used (g or ml) per volume (L)	Concentration [M] and [mg/L]	Cost
1	Sodium Hydroxide $NaOH$ (Caustic Soda)	40.00	40 g per 1 litre of D.I. water	1; 40,000	$0.60/kg at 50% (Flochem, Guelph)
2	Sodium Bicarbonate $NaHCO_2$	84.01	84.01g/1 litre	1; 84,010	$0.55/kg at 8% (Flochem, Guelph)
3	Hydrochloric Acid HCl	36.5 (1.18 SG)	441.65 g/L	4.03; 124,767	$0.60/kg (estimated)
4	**Coagulant # 1** Aluminum Chloride Hydroxide – (30-60%) - Nalco 8187 Cationic Charge $Al^2ClH_9O_7$	50 % (w/w)	1 ml of stock solution per 100 ml of water	5,000 [mg/L]	24 kg at $15.14 per kg = $363.36 272 kg at $6.64 per kg =$1,806.08
5	**Coagulant # 2** Poly(diallyldimethylammonium chloride) - Sigma Aldrich Cationic Charge $(C_8H_{16}Cl_N)_n$	50 % (w/v)	1 ml of stock solution per 100 ml of water	2,000 [mg/L]	4 L at $143 = 35.75 $/kg
6	**Coagulant # 3** Chitosan from shrimp shells, ≥75% (deacetylated) Water insoluble, mix with acetic acid [1 M] 10 mg/mL	NA	NA	NA	[1]21 $/kg (Gupta et al., 2009)
7	**Coagulant # 4** PolyGlu from soybean, natural product. PGα21Ca	NA	NA	NA	20 Kg Bag = $400 – 350 Depending on bags

[1]Bulk prices not available, only for lab scale use.

Appendix C2 Sample Calculations and Dosing Example

1. Hydrochloric Acid – HCL

Volume of stock solution = 225 mL = V_1

Normality = 12.1 N

1 M HCl = 1 N HCl therefore 12.1 N HCl = 12.1 M HCl

Find concentration in % by V/V

Molarity = Mass/Molar Mass

Mass = (Molarity)*(Molar Mass)

Mass = (12.1 mole/L)*(36.5g/mole) = 441.65 g/L

Conc. in % = (Mass/S.G.)/1000

Conc. in % = (441.65g/L)/(1.18g/ml * 1000ml/L) = 0.3743 or 37.43%

Conc. in ppm = 37.43% *10,000 = 374,300 ppm

V_2 = 675 ml

Concentration of diluted sample = ? = C_2

$C_2 = V_1C_1/V_2$ = (225 mL)(12.1 M)/(675 mL)

= 4.03 M or 124,767 ppm

2. Coagulant # 1 (NALCO #8187)

Properties: Charge – Cationic, Formula – $Al^2ClH_9O_7$**, Molecular Weight – 210.48**

Concentration = 50% => 50% x 10,000 = 500,000 ppm = C_1

Volume of stock solution = 1 mL = V_1

Volume of water = 100 mL = V_2

Concentration of diluted sample = ? = C_2

$C_2 = V_1C_1/V_2$ = (1 mL)(500,000)/(100 mL)

= 5,000 ppm

3. Coagulant # 2 (SIGMA-ALDRICH)

Properties: Charge – Cationic, Formula – (C8H16ClN)n,

Molecular Weight – 400,000-500,000 (high molecular weight), CAS Number 26062-79-3

http://www.sigmaaldrich.com/catalog/product/aldrich/409030?lang=en&region=CA

Concentration = 20% => 20% x 10,000 = 200,000 ppm = C_1

Volume of stock solution = 1 mL = V_1

Volume of water = 100 mL = V_2

Concentration of diluted sample = ? = C_2

$C_2 = V_1C_1/V_2$ = (1 mL)(200,000)/(100 mL) = 2,000 ppm

4. Chitosan – Shrimp shells (SIGMA-ALDRICH)

https://www.sigmaaldrich.com/catalog/substance/chitosan12345901276411?lang=en&region=CA

Biological source	from shrimp shells
assay	≥75% (deacetylated)
form	powder or flakes
solubility	acetic acid: water: soluble10 mg/mL, hazy (with extensive sonication)
	H_2O: insoluble
	organic solvents: insoluble
bulk density	0.15-0.3 g/cm^3
CAS Number	9012-76-4

Preparation: 500 mg of Chitosan into 500 mL of 1% (v/v) Acetic Acid

Thus, Chitosan/Acetic Acid Mixture concentration is 1000 mg/L

5. PolyGlu

Poly-Glu

1. Name of Product	PGα21Ca (PG alfa twenty-one CA)
2. Product Identification	
Single/Multiple Discrimination	Mixture
Chemical Name	Water Treatment Agent PGα21Ca
Major Component	Calcium sulfate 70 ~ 80 % Calcium carbonate 10 ~ 20 % Polyglutamic acid 1 ~ 10 % Sodium carbonate 1 ~ 10 % Others
Chemical Formula	$CaSO_4$ Ca_2CO_3 $(HOOC\text{-}CHCH_2CH_2COONa)n$ Na_2CO_3 $Al_2\ SO_4$ Others
H. S. code	3824.90-000

Preparation: The powder was mixed directly into the Jar Testing jar.

For example, to achieve a dosage of 100 mg/L for dosing, 100 mg of Poly-Glu was added to 1,000 mL (1 L) of the wash-water sample.

Jar Test Dosing Example – Nalco 8187

Test Dosage of 100 mg/L (ppm) on 1,000 mL of wash-water?

C1V1 =C2V2 (use the concentration equation as used above)

C1 = 5,000 mg/L, Concentration of prepared Nalco 8187 Coagulant chemical

V1 = ? mL, volume needed to achieve 100 mg/L of dosing in 1,000 mL of wash-water

C2 = 100 mg/L, desired concentration in wash-water sample

$V2 = 1{,}000$ mL of wash-water

$C1V1 = C2V2 \Rightarrow (5{,}000 \text{ mg/L})(V1) = (100 \text{ mg/L})(1{,}000 \text{ mL}) \Rightarrow \underline{V1 = 20 \text{ mL}}$

Therefore, 20 mL of prepared coagulant was added to 1,000 mL wash-water to achieve a final concentration of 100 mg/L.

Appendix D. Equipment and Suppliers

Appendix D1 Detailed Specification for Centrifuge and DAF (with dewatering)

Table D1-1: Centrifuge Specification and Price

Parameter	Dimension	Unit(s)
Feed Capacity	60 – 120; 15 – 30	usgpm; m^3/hr
Make and Model	FLOTTWEG DECANTER – C3E4	
Material	Duplex stainless steel, 1.4571 (AISI 316 Ti),	
Length	2.98	m
Width	0.94	m
Height	0.9	m
Gross Weight	1735	kg
Motor for bowl drive	25; 18.5	hp; kW
Motor for scroll drive FLOTTWEG SIMP-DRIVE®	5; 4	hp; kW
Total Power Demand	22.5	kW
Cost	220,000*	$
Quote obtained from Vector Process Equipment Inc., Mississauga, Ontario (2013) *Cost normalized to 2018 price index		

Table D1-2: DAF Equipment Specification and Price

Parameter	Dimension	Unit(s)
Peak Flow	70;16	Usgpm; m^3/hr
Length	3.65	m
Width	1.9	m
Height	1.9	m
Weight	850	kg
Wet weight	5000	kg
Skimmer Motor + Recirculation Pump	0.34 + 5.4 = 5.7; 4.25	hp; kW
DAF Cost + Inline mixer	60,000	$
Dewatering Equipment – Centrifuge – dewater to 4% upon optimum conditions	110,000	$
Total cost of system	170,000*	$
Quote obtained from H2Flow Equipment Inc., Concord, Ontario NOTE: System doesn't include polymer addition systems. *Cost normalized to 2018 price index		

Appendix D2 Equipment Types

Figure D2-1: Example of a Stationary Screen (www.lycomfg.com) which uses wedge-wire screens over wire mesh to reduce clogging.

Figure D2-2: Example of a Rotating Screen (www.lycomfg.com). Wastewater enters from behind (solids and liquids), as the drum rotates the water drains through the screen, while solids exit from the front.

Figure D2-3: Example of a Vibrating Round Screen (www.sweco.com), where the particles are retained by the top sieve and ejected to the side while the liquid fall to the bottom tray to flow out to the side.

Figure D2-4: Example of Centrifuge for solid-liquid separation (www.sweco.com), works by using high centripetal forces to separate the solids from the wastewater.

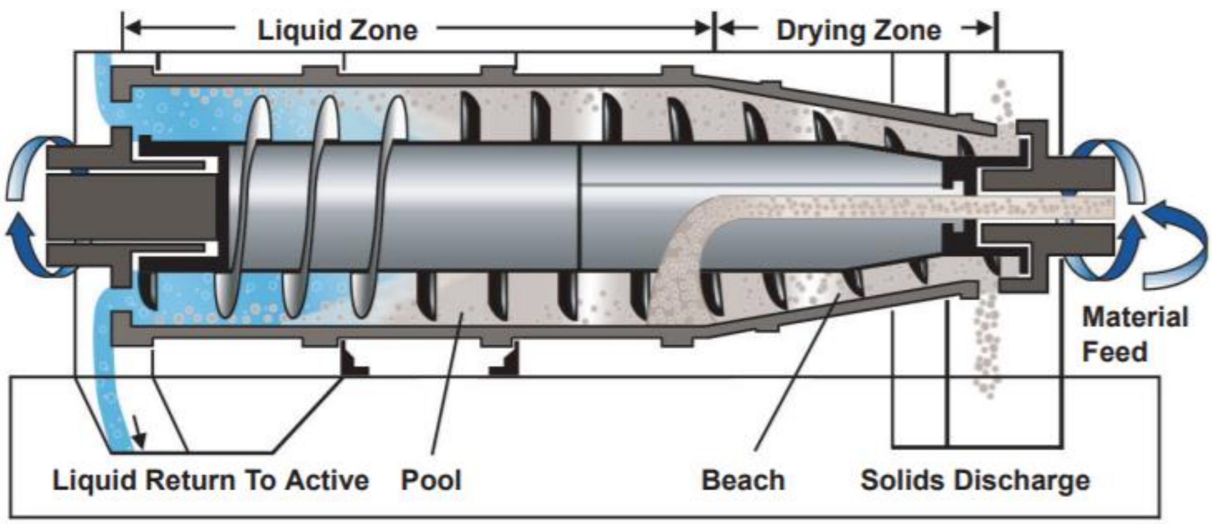

Figure D2-5: Schematic diagram of a centrifuge to show important parts and operations (www.sweco.com).

Figure D2-6: Example of a Dissolved Air Flotation unit from the Alpha manufacturer (www.h2flowdaf.com).

Figure D2-7: Example of Hydrocyclone solid-liquid separation (http://www.muddyriver.ca/hydrocyclones/).

Figure D2-8: Example of an Electrocoagulation reactor (www.google.com/images), very similar to DAF, as floated/separated solids require additional dewatering either by centrifuge or filter press.

Appendix E. Data Sources

The data collected and sourced for this study consist of water quality data sampled and analyzed during the study period, as highlighted in the first publication. While additional data sourced from OMAFRA was used to fill any gaps in the study and further expand characterization, as indicated in the second publication. The data collected, and the work competed by the author is available upon request from Dr. Richard G. Zytner (rzytner@uoguelph.ca). Sensitive details relating to study participants have been removed to ensure confidentiality of the study participants. Also, some data may be averaged to protect study participants processes and trade secrets. The raw data from OMAFRA is not available for public due to the confidential agreement. A version with less sensitive OMAFRA data/water quality parameters was mixed with the collected data and is represented in the third publication of the dissertation.

Appendix F. Treatment Prediction and Costing Toolkit

Appendix F1 Screenshots of the excel worksheet

Last Modified:	**June 20, 2018**
Purpose:	**The purpose of this excel sheet is to provide user with a toolkit that can be used to (1) predict the raw wash-water/wastewater quality based on the fruit and vegetable type in addition to the process (washing versus washing with processing), (2) predict the water quality of treated waters under studied treatment in addition to process, and (3) estimate the cost of treatment in ($/m^3) using capital and variable costs of different treatments studied. The treatment feasibility tool (2) and costing tool (3) are combined into a single tool. The three tools are included in this toolkit to assist in determining raw wash-waters quality, treatment potential, and associated costs of implementing the treatments.**
Overview:	**The overall study objective was to investigate fruit and vegetable wash-water/wastewater treatment and reuse potential. This was separated into three different tasks, first to investigate the wash-water quality parameters, second to study treatment feasibility by testing bench-scale treatments and understanding full-scale treatments, and finally modelling the results of bench-scale and full-scale treatments into predictive tools for end users. Cost-benefit analysis was added to complete the overall feasibility of treatments. To aid in assessing wash-water treatment potential based on treatment, process, and raw water quality parameters. The selected models can provide another useful tool for decision makers and stakeholders in understanding which water treatment technologies can help them achieve reduction in wastewater contaminants, such as TSS and BOD. Whether it can be used for reuse or disposal, and to understand the meeting of regulatory effluent water quality limits. Costing is combined to extend the useful of the overall model.**
Sheets:	**The worksheets are divided into three categories, (1) overview, (2) TSS, TN, TP, NH4-N, BOD, and COD treatment prediction and costing worksheets, and (3) model and costing calculations, and (4) water quality regulations.**
Disclaimer:	**The tools provide information and feasibility analysis of wash-water/wastewater treatments based on mathematical models which are associated with certain base conditions, assumptions and inherent errors. As such, high level of precaution is necessary in understanding the type of wash-waters/wastewater studied and interpreting results of the models. In addition, the costing is estimated based on the best available information at the time which are subjected to change and require detailed analysis if implementation is to be considered. These tools need to be used with sound engineering and technical expertise as they may be used to make critical operation/business decisions. The authors are not responsible or liable for any financial loss caused as results of use of this tool to make wastewater treatment decisions, as wastewater treatment is very complicated and requires thorough design and implementation by a professional engineering firm.**

An overview is provided before the user starts using the worksheet.

The Power-Rank model can be used to estimate water quality of raw wash-waters/wastewater from fruit and vegetable operations. The model to predict wash-water from washing operations is shown on the left side, marked by W process type. While, the model for washing and processing wash-waters is shown on the right, marked WP.

Power-Rank Models for Predicting Raw Wash-water/Wastewater Quality

Process Type	W		Process Type	WP	
Select Fruit or Vegetable	Boston Lettuce		Select Fruit or Vegetable	Carrot	
Washing Process Operation Type			Washing and Processing Operation Type		
Water Quality Parameter	**Average**	**Standard Deviations**	**Water Quality Parameter**	**Average**	**Standard Deviations**
TSS	138	14	TSS	1,005	575
TS	1,022	58	TS	4,060	2,091
TDS	572	52	TDS	2,555	1,447
TP	2.6	0.1	TP	8.8	7.0
TN	7.2	0.4	TN	16.3	3.7
COD	263	38	COD	4,044	3,160
BOD	60	15	BOD	930	1,379
COND	0.750	0.039	COND	0.97	0.37
NH4-N	0.5	0.0	NH4-N	2.7	2.8

*All units are in mg/L except for COND which is in us/cm.

Nine different water quality parameters are determined.

Both, average and standard deviation are listed.

TSS model inputs include process type information and concentration of raw water quality parameters.

TSS model inputs parameter range is also provided to ensure input is in valid range.

TSS Model

Raw Wash-water quality parameters	Inputs	Units	Range				
Process	W		W or WP				
Total Solids	2500	mg/L	470 - 13,800				
Total Nitrogen	5	mg/L	0.90 - 101				
Treated Wash-water quality parameter based on Treatment	**Output**	**Units**	**Meet Sanitary Sewer**	**Meet PWQO**	**Rank**	**Range**	
			350	**25**			
For the following treatment:			**mg/L**	**mg/L**		**Low***	**High**
Bench-Scale							
Centrifuge	1,370	mg/L	>Limit	>Limit	6	634	2,106
Dissolved Air Flotation	25	mg/L	<Limit	<Limit	1	-	1,472
Electro-coagulation	2,189	mg/L	>Limit	>Limit	5	1,453	2,500
Hydro-cyclone	3,665	mg/L	>Limit	>Limit	6	2,500	2,500
Sieve (Screening)	5,141	mg/L	>Limit	>Limit	7	2,500	2,500
Settling with Coagulation and Flocculation	25	mg/L	<Limit	<Limit	1	-	1,472
Full-Scale							
Settling - 1 Tank	2,927	mg/L	>Limit	>Limit	4	2,191	2,500
Settling - 3 Tanks in series	25	mg/L	<Limit	<Limit	1	-	1,472
Settling - 1 Tank with Grasslands	25	mg/L	<Limit	<Limit	1	-	1,472
Settling with biological treatment	632	mg/L	>Limit	>Limit	1	-	1,368
Membrane Bio-Reactor	N/A	mg/L	>Limit	>Limit	N/A	#VALUE!	#VALUE!
Pond	4,403	mg/L	>Limit	>Limit	1	2,500	2,500

All treatment results are show.

Meeting of regulatory limit are indicated.

Treated water quality range is provided.

Costing Analysis - Cost of Treatment in $/day

Operating Costs and Components

No.	Costing Inputs	Value	Units	Comments
1	Costs			
1.1	Cost of Water and Wastewater Services	2.31	$/m^3	
1.2	Cost of Electricity (average of on- and mid-peak)	0.12	S/kWh	
2	Facility Requirements			
2.1	Operation Time	10	hr/day	
2.2	Flow	50	m^3/day	Current Water Usage
	Operation day in a year	150	days	
2.3	Current Electrical Demand	100	kWh	
2.4	Water and Wastewater costs incurred by facility	115.5	$/day	
2.5	Electricity costs incurred by facility	120	$/day	
3--6	Chemical Cost and Demand			
3.1	Acid Used? (Yes or No)	No		
3.2	Acid Cost	0.6	$/kg	
3.3	Acid Dosage Demand	100	mg/L	
3.4	kg of Acid per day	0	kg/day	
3.5	Cost of Acid per day	0	$/day	
3.6	Cost of Acid per cubic meter of water adjusted	0	$/m^3	
4.1	Base Used? (Yes or No)	Yes		
4.2	Base Cost	0.6	$/kg	
4.3	Base Dosage Demand	20	mg/L	
4.4	kg of Base per day	1	kg/day	
4.5	Cost of Base per day	0.6	$/day	
4.6	Cost of Base per cubic meter of water adjusted	0.01	$/m^3	
5.1	Coagulant Used? (Yes or No)	No		
	Cost of Coagulants			
5.2	Nalco 8187	15.14	$/kg	
5.3	Sigma	35.75	$/kg	
5.4	Chitosan	21	$/kg	
5.5	PolyGlu	20	$/kg	
	Coagulant Demand			
5.6	Select Coagulant	Nalco 8187	-	
5.7	Coagulant Dosage Demand	100	mg/L	
5.8	Cost of Coagulant per day	0.00	$/day	
5.9	Cost of Base per cubic meter of water adjusted	0.00	$/m^3	
6	Electrodes required for Electrocoagulation	Yes		
	Cost of Electrodes			
6.1	Alum	2.71	$/kg	
6.2	Iron	0.3	$/kg	
6.3	Select Electrode	Alum		
6.4	Dissociation Rate	0.51	kg/m^3	Typical Range - 0.01 to 0.31 kgAl/m^3
6.5	Electrode consumption per cubic meter treated	1.38	$/m^3	
6.6	Electrode consumption per day	69.105	$/day	

Utility costs included.

Facility flow and operating parameters are added by user. Chemical use can also be selected.

Operating Costs and Components (con't)				
No.	**Costing Input**	**Value**	**Units**	**Comments**
7	Pumping Costs? (Yes or No)	Yes		
2.2	Flow	50	m^3/day	
7.1	Head	20	m	
7.2	Efficiency	0.7		
7.3	Power Demand	18.5	kWh	
7.4	Cost per pump	10000	$	
7.5	Number of Pump Required	1		
7.6	Safety Factor	2		
7.7	Number of Pump - Design Requirement	2		
7.8	Total cost of Pumps	20000	$	
7.9	Cost per hour per pump	0.36	$/hr	
8	Cost per day per pump	3.64	$/day	
8.1	Cost per hour per pump per cubic meter of water pumped	0.01	$/m^3	
8.2	Cost of pumping per hour	0.73	$/hr	
8.3	Cost per day of pumping	7.28	$/day	
8.4	Cost of pumping per cubic meter	0.01	$/m^3	
9	Total Operating Costs			
2.4	Water and Wastewater costs incurred by facility	115.5	$/day	
2.5	Electricity costs incurred by facility	120	$/day	
3.5	Cost of Acid per day	0	$/day	
4.5	Cost of Base per day	0.6	$/day	
5.8	Cost of Coagulant per day	0	$/day	
6.6	Electrode consumption per day	69	$/day	
8.3	Cost per day of pumping	7	$/day	
9.1	Total Operating Costs	312	$/day	
9.2	Total Operating Costs	6	$/m^3	

Pumping costs.

Summary of operating costs. Total operating costs listed as cost per day ($/day) and cost per cubic meter of water treated ($/m^3).

Capital costing includes cost of treatment, amortization period, and interest rate can be modified as needed.

Capital Cost of Treatment							
10	Treatment	Capital Costs ($)	Comments	Annual Debt Service ($)	Cumulative Debt Service ($)	Annual Debt Service/Annual Flow ($/m^3 per year) based on days of operations per year	Cost per day under daily facility flow ($/day)
10.1	Centrifuge	220,000	180,000 to 220,000 (with dewatering)	28,491.01	284,910.06	3.80	190
	Dissolved Air Flotation	170,000	95,000 to 170,000	22,015.78	220,157.78	2.94	147
	Electro-coagulation	50,000		6,475.23	64,752.29	0.86	43
	Hydro-cyclone	20,000	Estimated	2,590.09	25,900.91	0.35	17
	Sieve (Screening)	50,000	20,000 to 125,000	6,475.23	64,752.29	0.86	43
	Settling with Coagulation and Flocculation	75,000	50,000 to 75,000	9,712.84	97,128.43	1.30	65
	Settling - 1 Tank	10,000	Estimated	1,295.05	12,950.46	0.17	9
	Settling - 3 Tanks in series	30,000	Estimated	3,885.14	38,851.37	0.52	26
	Settling - 1 Tank with Grasslands	10,000	Estimated	1,295.05	12,950.46	0.17	9
	Settling with biological treatment	250,000		32,376.14	323,761.44	4.32	216
	Membrane Bio-Reactor	500,000		64,752.29	647,522.87	8.63	432
	Pond	10,000	Estimated	1,295.05	12,950.46	0.17	9
10.2	Amortization Period	10	Years				
10.3	Interest Rate	0.05					
10.4	Annual Payment of Present Loan Amount (A/P)	0.130					

Annual debt service is calculated and normalized to dollar cost per cubic meter of water treated ($/m^3) and cost per day ($/day).

Capital and operating costs are summarized as cost per day ($/day).

11	Capital and Operating Cost of Treatment in $/day				
	Treatment	Capital cost ($/day)	Operating Cost without chemical/coagulant	Operating Cost including chemical/coagulant ($/day)	Total daily cost ($/day)
	Centrifuge	190	5		195
	Dissolved Air Flotation	147	5	5	156
	Electro-coagulation	43	5	6	54
	Hydro-cyclone	17	5		22
	Sieve (Screening)	43	5		48
	Settling with Coagulation and Flocculation	65	5	5	74
	Settling - 1 Tank	9	5		13
	Settling - 3 Tanks in series	26	5		31
	Settling - 1 Tank with Grasslands	9	5		13
	Settling with biological treatment	216	5		221
	Membrane Bio-Reactor	432	5		437
	Pond	9	5		13

Total daily costs show the amount of money needed to implement and run treatment.

These costs are compared with savings, resulting from reduced costs of water and wastewater services due to water reduction/recycling. In addition to reducing surcharges for exceeding regulatory water quality parameters, such as BOD and TSS.