Reclamation of Vegetable Processing Wastewater with a Sequencing Batch Reactor

by

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A Thesis
presented to
The University of Guelph

In partial fulfilment of requirements
for the degree of
Master of Applied Science
in Engineering

Guelph, Ontario, Canada

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An investigation was completed for nutrient and organic loading removal from vegetable processing wastewater. Vegetable processing wastewater was collected from two industrial partners. The sequencing batch reactor was selected as the treatment technology due to its versatility, with the system HRT chosen as the varying parameter to be tested. It was determined that the optimal conditions for organic loading and nutrient removal for Industrial Partner 1 were 2.5 h of aeration and 1.0 L, which equates to 20% of liquid exchange with a HRT of 30 h, obtaining removal efficiencies of 95%, 79% and 75% for COD, TKN and TP respectively. Confirmation studies were completed with Industrial Partner 2. Similar operational characteristics were used, but different removal efficiencies were obtained, confirming the need to optimize the process for every application. UV disinfection was also used for microbial removal for onsite water reuse.
Acknowledgement

I would like to take the time to thank my advisor Dr. Richard G. Zytner for giving me the opportunity to work with him. He has always given me the support that I needed and has helped me through every big and small problem that I have encountered.

I would like to thank my co-advisor Dr. Sheng Chang for giving me valuable advice throughout the project, and Dr. Keith Warriner for his expertise on microbial cell growth.

I would also like to thank all the help and support that Joanne Ryks and Ryan Smith has given me for laboratory support.

I would also like to thank my parents who love me unconditionally and have supported me throughout all my studies. To my brother who has always challenged me.

Finally, I would like to thank all my friends for providing me with their support. Without their understanding, tolerance, patience and love, I would not be where I am today – J. C., N.R., X. L., L. L., N. N., I. S., and V. N. It would be hard to imagine where I would be without you, so thank you all.

“Learn from yesterday. Live for today. Hope for tomorrow. The important thing is to never stop questioning” – Albert Einstein
# Table of Contents

Chapter 1: Introduction ............................................................................................................................ 1  
  1.1 Industrial Partners .............................................................................................................................. 3  
  1.2 Purpose of Study ................................................................................................................................. 4  
  1.3 Objectives ......................................................................................................................................... 5  
  1.4 Layout ............................................................................................................................................. 6  

Chapter 2: Literature Review .................................................................................................................... 7  
  2.1 Background ...................................................................................................................................... 7  
    2.1.1 Problems from Vegetable Processors .......................................................................................... 7  
    2.1.2 Effect of Nutrients on the Environment ................................................................................. 8  
    2.1.3 Municipal By-laws ....................................................................................................................... 9  
    2.1.4 Solids and Nutrients Removal .................................................................................................. 10  
      2.1.4.1 Total Solids ....................................................................................................................... 11  
      2.1.4.2 Chemical or Biological Oxygen Demand .................................................................. 11  
      2.1.4.3 Total Kjeldahl Nitrogen .................................................................................................. 11  
      2.1.4.4 Total Phosphorus .......................................................................................................... 13  
  2.2 Available Technology ....................................................................................................................... 14  
    2.2.1 Chemical ................................................................................................................................... 18  
    2.2.2 Physical .................................................................................................................................... 18  
    2.2.3 Biological ................................................................................................................................. 18  
      2.2.3.1 Upflow Anaerobic Sludge Blanket ............................................................................... 18  
      2.2.3.2 Membrane Bioreactor (MBR) .......................................................................................... 19  
      2.2.3.3 Anaerobic Packed Bed ..................................................................................................... 19  
      2.2.3.4 Anaerobic Sequencing Batch Reactor ........................................................................... 20  
  2.3 Aerobic Sequencing Batch Reactor ................................................................................................... 20  
    2.3.1 General Operation ...................................................................................................................... 22  
    2.3.2 Parameters Affecting Removal Efficiency .............................................................................. 25  
      2.3.2.1 Temperature .................................................................................................................... 25  
      2.3.2.2 Dissolved Oxygen ......................................................................................................... 25  
      2.3.2.3 pH .................................................................................................................................... 26  
      2.3.2.4 Sludge Properties ............................................................................................................. 26  
      2.3.2.5 Hydraulic Retention Time ............................................................................................... 27  
    2.3.2.5 Overall General Parameters ............................................................................................... 28  
  2.4 Disinfection ..................................................................................................................................... 30  
    2.4.1 Chlorine Disinfection ............................................................................................................... 31  
    2.4.2 Advanced Oxidation ................................................................................................................. 32  
    2.4.3 Ultraviolet Disinfection .......................................................................................................... 33  
    2.4.4 Other Methods ....................................................................................................................... 35  
      2.4.4.1 Electrochemical .............................................................................................................. 35  
      2.4.4.2 Cavitation ....................................................................................................................... 35  
      2.4.4.3 Organic Acids ................................................................................................................ 36  
  2.5 Overview ......................................................................................................................................... 36  

Chapter 3: Methodology .......................................................................................................................... 38  
  3.1 Collection of Vegetable Processing Wastewater ............................................................................. 38  
  3.2 Overall Design of Experiments ....................................................................................................... 39
7.1 Raw Data .............................................................................................................. 119
7.2 Sample Calculations ............................................................................................ 127
  7.2.1 Biological Oxygen Demand Range .............................................................. 127
  7.2.2 BOD$_5$ Data .................................................................................................. 128
  7.2.3 Payback Period .............................................................................................. 129
  7.2.4 UV Disinfection ............................................................................................ 130
  7.2.5 Statistical Analysis of IP1 and IP2 (McBean and Rovers, 1998) ............... 131
  7.2.6 SRT and MLSS .............................................................................................. 135
List of Tables

Table 1 – Problems with Vegetable Wastewater ................................................................. 7
Table 2 – Sanitary Sewer Discharge Limit ........................................................................ 9
Table 3 – Storm Sewer Discharge Limit ........................................................................... 10
Table 4 – COD Removal Efficiencies of Various Technologies ........................................ 16
Table 5 – Nutrient Removal Efficiency of Various SBR Systems ...................................... 24
Table 6 – Major Parameters of Various Experiments ......................................................... 29
Table 7 – General Operating Conditions .......................................................................... 30
Table 8 – Aeration Experiments ....................................................................................... 40
Table 9 – Overview of Experiments .................................................................................. 41
Table 10 – Aeration Experiments ..................................................................................... 41
Table 11 – Liquid Exchange Experiments ........................................................................ 41
Table 12 – Equipment Used for SBR ................................................................................ 42
Table 13 – Equipment Used for Analysis .......................................................................... 43
Table 14 – Disposable Equipment for Analysis ................................................................ 44
Table 15 – Equipment used for UV Disinfection ................................................................. 45
Table 16 – Disposables for UV Disinfection ..................................................................... 45
Table 17 – Day 1 to 51 of Acclimation Data ..................................................................... 58
Table 18 – Day 1 to 62 of Acclimation Data ..................................................................... 58
Table 19 – BOD₃/COD Ratio of Various Wastewater ........................................................ 60
Table 20 – COD Calibration ............................................................................................. 60
Table 21 – TKN Calibration ............................................................................................. 60
Table 22 – TP Calibration ................................................................................................. 61
Table 23 – Dates of Data collection ................................................................................... 62
Table 24 – Experiment 1-1: 450 min Aeration and 1.5 L Drawn ........................................ 64
Table 25 – Experiment 1-2: 270 min Aeration and 1.5 L Drawn ........................................ 64
Table 26 – Experiment 1-3: 150 min Aeration and 1.5 L Drawn ........................................ 65
Table 27 – Experiment 1-4: 150 min Aeration and 1 L Drawn ........................................... 65
Table 28 – Experiment 1-5: 150 min Aeration and 2 L Drawn ........................................... 66
Table 29 – Experiment 1-6: 150 min Aeration and 2.5 L Drawn ........................................ 66
Table 30 – Summary of Results ....................................................................................... 76
Table 31 – Industrial Partner 2 Experiment Conditions ..................................................... 86
Table 32 – Experiment 2-1: 4.5 h of Aeration and 1.5 L of Liquid Drawn ......................... 87
Table 33 – Experiment 2-2: 2.5 h of Aeration and 1.5 L of Liquid Drawn ......................... 87
Table 34 – SBR Removal Efficiency with Various HRT ..................................................... 92
Table 35 – Cycle Time for Experiment 2-2 of Industrial Partner 2 ..................................... 95
Table 36 – Required UV Dose Delivery ............................................................................ 100
Table 37 – Original Concentration of B. subtilis ............................................................... 100
Table 38 – Concentration of B. subtilis after UV ............................................................... 101
Table 39 – Flow Rate of Industrial Partner 2 in 2010 ......................................................... 103
Table 40 – Payback Period Calculation ............................................................................ 104
Table 41 – Raw Data for COD, TKN and TP ................................................................. 119
Table 42 – Absorbance Values for Various Experiments from Industrial Partner 1 ........ 126
Table 43 – Mixed Liquor Suspended Solids Data During Acclimation ............................. 126
Table 44 – Cost ................................................................................................................ 130
Table 45 – IP1 and IP2 Data for COD ................................................................. 132
Table 46 – IP1 and IP2 Data for TP ................................................................. 133
Table 47 – IP1 and IP2 Data for TKN ............................................................... 134
List of Figures

Figure 1 – Types of Technologies Available for Different Wastewater ........................................... 17
Figure 2 – Nutrient Removal Process for a Sequencing Batch Reactor ........................................... 22
Figure 3 – General Configuration of a SBR .................................................................................. 22
Figure 4 – General Collimated Beam .......................................................................................... 34
Figure 5 - Configuration of SBR ...................................................................................................... 43
Figure 6 – Collimated Beam Configuration .................................................................................. 45
Figure 7 – Removal Efficiency During Acclimation ..................................................................... 57
Figure 8 – Before and After COD Concentration for Experiment 1-1 to 1-6 ............................ 67
Figure 9 – Average COD Removal Efficiency with 95% Confidence Interval ............................. 68
Figure 10 – Before and After TKN Concentration for Experiment 1-1 to 1-6 ........................... 69
Figure 11 – Average TKN Removal Efficiency with 95% Confidence Interval .......................... 71
Figure 12 – Before and After TP Concentration for Experiment 1-1 to 1-6 ............................... 72
Figure 13 – Average TP Removal Efficiency with 95% Confidence Interval .............................. 72
Figure 14 – Average Removal Efficiencies for Experiments 1-1 through 1-6 ............................ 74
Figure 15 – Effect of Aeration on the Removal Efficiency ............................................................ 77
Figure 16 – Effect of the Liquid Drawn on the Removal Efficiency ............................................. 78
Figure 17 – Before, After and Limit of COD Concentration for Experiment 1-2 ..................... 80
Figure 18 – Before, After and Limit of TKN Concentration for Experiment 1-2 ...................... 80
Figure 19 – Before, After and Limit of TP Concentration for Experiment 1-2 ......................... 80
Figure 20 – Before, After and Limit of COD Concentration for Experiment 1-3 ................. 81
Figure 21 – Before, After and Limit of TKN Concentration for Experiment 1-3 .................. 82
Figure 22 – Before, After and Limit of TP Concentration for Experiment 1-3 ...................... 82
Figure 23 – Before, After and Limit of COD Concentration for Experiment 1-4 .................. 83
Figure 24 – Before, After and Limit of TKN Concentration for Experiment 1-4 ................. 84
Figure 25 – Before, After and Limit of TP Concentration for Experiment 1-4 .................... 84
Figure 26 – COD Concentration for Experiment 2-1 and 2-2 for Industrial Partner 2-2 .......... 89
Figure 27 – TKN Concentration for Experiment 2-1 and 2-2 for Industrial Partner 2-2 .......... 90
Figure 28 – TP Concentration for Experiment 2-1 and 2-2 for Industrial Partner 2 .............. 91
Figure 29 – Experiment 1-2 and 2-1 Results for IP1 and IP2 ....................................................... 96
Figure 30 – Experiment 1-3 and 2-2 Results for IP1 and IP2 ....................................................... 96
List of Equations

Equation 1 – Oxidation of Ammonium to Nitrite (Sharma an Ahler, 1977) ................................. 11
Equation 2 – Oxidation of Nitrite to Nitrate (Sharma and Ahler, 1977) ................................. 11
Equation 3 – Conversion of Nitrate to Nitrite with Methanol (Metcalf and Eddy, 1972) ........ 12
Equation 4 – Conversion of Nitrite to Nitrogen Gas with Methanol (Metcalf and Eddy, 1972) .. 12
Equation 5 – Overall Conversion (Metcalf and Eddy, 1972) .................................................. 12
Equation 6 – Minimum DO Depletion .................................................................................. 48
Equation 7 – Maximum DO Depletion .................................................................................. 48
Equation 8 – Determination of BOD₅ Concentration ............................................................ 48
Equation 9 – Determination of UV Fluence .......................................................................... 51
Equation 10 – Determination of Time Required for Dosage .................................................. 51
Equation 11 – Reflection Factor (Bolton and Linden, 2003) ................................................. 52
Equation 12 – Water Factor (Bolton and Linden, 2003) ......................................................... 52
Equation 13 – Divergence Factor (Bolton and Linden, 2003) .................................................. 52
Equation 14 – Germicidal Irradiance (Bolton and Linden, 2003) ............................................. 53
Nomenclature

AOP – Advanced Oxidation Process
APB – Anaerobic Packed Bed
ASBR – Anaerobic Sequencing Batch Reactor
ATP – Adenosine Triphosphate
BOD$_5$ – Biological Oxygen Demand for 5 Days
COD – Chemical Oxygen Demand
CT – Concentration Time
D$_{10}$ – UV dosage required for 1 log removal
DO – Dissolved Oxygen
EPR – Enhanced Phosphorus Removal
F$_{\text{critical}}$ – value obtained from an F table
GRAS – Generally Regarded As Safe
IP1 – Industrial Partner 1
IP2 – Industrial Partner 2
MBR – Membrane Bioreactor
MLSS – mixed liquor suspended solids
PHA – poly(hydroxylalkanoates)
Poly-P – poly phosphate
SBR – Sequencing Batch Reactor
sBOD – Soluble Biological Oxygen Demand
sCOD – Soluble Chemical Oxygen Demand
SD – Standard Deviation
SRT – Solid Retention Time
t* – t-test statistic
t$_c$ – value obtained from a t-distribution table
TKN – Total Kjeldahl Nitrogen
TP – Total Phosphorus
TSS – Total Suspended Solids
TTHM – Trihalomethane
UASB – Upflow Anaerobic Sludge Blanket
UF – Ultrafiltration
USEPA – United States Environmental Protection Agency
UV – Ultraviolet
VFA – Volatile Fatty Acids
Chapter 1: Introduction

The demand for safe and reliable food sources will increase with increasing population throughout the world. Water is essential for the growing and processing of food. Depending on the type of operations, the use of the water varies. Vegetable processing is one of the most important food processing operations. Through the processing of vegetables, wastewater is generated from the washing, peeling and cutting processes, and then finally the cleaning of the machinery.

When vegetables are cleaned and processed, vegetable residue is transferred into the water in both solid and dissolved form. This leads to a high organic loading and nutrient concentrations. The organic loading can cause a high depletion of dissolved oxygen (DO) in the receiving body of water through biochemical oxygen demand (COD), which impacts a variety of larger organisms, such as fish.

Nutrients such as nitrogen and phosphorus content also cause water quality issues. The nitrogen content in the wastewater refers typically to the ammonia, nitrite, nitrate and organic nitrogen levels. In general, the nitrogen content within the water is calculated as the total Kjeldahl nitrogen (TKN) and the phosphorus is counted as the total phosphorus (TP). If the nutrient in the wastewater is to be directly discharged into a waterbody without processing, it could potentially cause eutrophication. To prevent eutrophication from occurring, municipalities create By-laws which limits the concentration of nutrients and organic loading from being discharged. When limits are exceeded, a surcharge is incurred.
The three main types of processes that can be implemented to prevent surcharges would be chemical, physical and biological. Chemical precipitation would be the addition of a coagulant and flocculant to allow the organic particles to coalesce into larger sized floc particles, making it easier for them to settle to the bottom of the reactor. A physical process would be in the use of a centrifuge to separate the organic solids from the liquid wastewater. Biological process would include the use of microbes to remove the dissolved nutrients and organic loading from the wastewater.

The surcharges that are incurred are based on both the quality and quantity of the discharged wastewater. Reduction of the nutrient and organic loading would improve the quality of the vegetable processing wastewater. The quantity of the wastewater would require the facility to reduce the wastewater that is being discharged. By treating the wastewater onsite, for potential reuse, it would permit the diversion of the wastewater from the local wastewater treatment plant.

Water usage could also limit the amount of products that are made available as well. In Ontario, the last peach canning operation was closed in 2008. The two main markets that exist for fresh fruit would be the pick-your-own market and the canning market. However, certain fruits are only meant to be canned. Peaches that are meant for canning are much firmer (University of Guelph, 2010). With the closing of the last factory, it would create a strain on the farmers that have focussed fruits specifically for the canning industries since fruit trees take multiple years to grow.
1.1 Industrial Partners

Wastewater from two vegetable food industrial partners was studied. Wastewater from Industrial Partner 1 (IP1) was collected at a collection point prior to discharge into the sanitary sewer. The wastewater from Industrial Partner 2 (IP2) was collected after the processing treatment of carrots and potatoes but prior to the current onsite treatment. Wastewater from both facilities was collected and fed into the laboratory treatment system where the removal efficiency was determined.

Industrial partner 1 is located within the Municipality of Peel, specifically within the City of Mississauga. The facility processes vegetables, such as beets, carrots, cassava and shredding of iceberg lettuce to name a few. The vegetables are subjected to washing, peeling and cutting. The facility currently does minimal treatment of wastewater by using simple settling that removes mainly the large particles of organic matter. These solids are then shipped out as cattle feed. The facility also does not contain any water reuse planning. The facility provides supplemental disinfection of the water with dilute citric acid prior to processing the treatment of the vegetables.

Industrial partner 2 is located within the City of Toronto. The facility mainly processes carrots and potatoes. The processing of the potatoes would include washing, peeling and melon balling. Carrots are washed and peeled and potentially shredded as well. The facility also contains a line which peels the outer layer of onions and a line which peels and cuts apples. However, the predominant amount of wastewater produced is still from the potato and carrot peeling line. The facility already has an onsite treatment for the vegetable processing wastewater but is still unable
to meet the sanitary sewer discharge limits. Wastewater from Industrial Partner 2 was collected after the processing of the vegetables but before the onsite treatment.

Other than having an extremely high biological oxygen demand (BOD₅), vegetable processors also have site-specific problems as well, that must be considered when developing a treatment process. For example, when potatoes are processed, the starch released to the wastewater creates an excessive amount of foaming. Industrial Partner 2 adds a de-foaming agent to the potato processing wastewater. Industrial Partner 1 however does not currently control the foam that is created when processing potatoes or cassava, however, during collection of weekly wastewater, it is apparent that there is a foaming problem.

1.2 Purpose of Study

The purpose of this study is to treat the vegetable processing wastewater to avoid current and future surcharges. However, there is currently not one technology that could reduce solid and nutrient concentrations for all types of vegetable processing wastewater. As such, the goal of the research is to sample from one location, develop a treatment process and then determine if the technology is viable by sampling the second location. The two main goals are to reduce the nutrient and organic loading concentration of the wastewater and to reduce the amount of wastewater that is discharged.

The first objective would be to reduce the organic loading and nutrient concentration below the sanitary sewer discharge limit in order to avoid any surcharge fee. The second objective would be to reduce the nutrient concentration to below the storm sewer discharge limit which will avoid any future surcharge fees when and if municipalities reduce the allowable discharge limit.
Reducing the nutrient concentrations to below the storm sewer discharge limit could also avoid having the wastewater enter the municipals wastewater facility. Reducing the nutrient concentration to below the storm sewer and reusing that water within the facility for another process would effectively reduce the quantity of wastewater that is being discharged. This would also reduce the need to use new freshwater for various processes. However, to ensure that the recycled water does not impose any microbial threat, it must be disinfected before being reused within the facility. The disinfection process will require an ultraviolet system to attain a log 5 removal.

1.3 Objectives

The two main objectives to this study are the reduction of nutrient and organic loading concentrations and the reduction of fresh water usage. Surcharges are based on the concentration of the nutrient and the flow from the facility into the treatment plant. If nutrient concentrations discharged are less than the allowable amount, it would be possible to avoid a surcharge fee. However, the nutrient concentration cannot be diluted prior to disposal. Allowance limits are also dependent on the location of the facility and are site specific, subject to municipal regulations.

Conservation of water usage is for both the environment and for monetary means. Agriculture accounts for the main portion of fresh water usage, which could go as high as 85% for some countries (Environment Canada, 2009). Even within North America, there could be times when fresh water is not available for use, specifically with the southern States of America (USEPA, 2013). A percentage of water that is used for irrigation does infiltrate back into the water table, but it is not 100%. The cost of water within Canada is about $0.31/m³ as compared to Germany
that charges $2.16/m³ (Environment Canada, 2011). If the cost of water were to increase (City of Guelph, 2009), this would create a large financial strain on institutions that rely heavily on the use of water. Water recycling should be possible if the absorbance of the effluent wastewater is low and if disinfection was to be implemented.

1.4 Layout

The thesis is broken down into 3 main sections. The first section, literature review, will outline the reasons for conducting the research, the problems that are commonly incurred and current solutions. The second section, methodology, will outline all the materials that were used for data collection. The third main section, results and discussion, will give suggestions and conclude if the results are to be used for future research. Further, there is a section on design and cost, which will outline some of the reasons for or against building the SBR. Finally, the thesis will give a brief conclusion based on the research.
Chapter 2: Literature Review

This section will add insight to the importance of organic loading and nutrient removal from vegetable processing wastewater.

2.1 Background

The water that is used to process fruits and vegetables can be divided into 2 categories. Water that is used to rinse off the soil of the fruits and vegetables is categorized as washwater, where water that is involved in the process of slicing, dicing, shredding and other processes is characterized as wastewater. This project concerns the treatment of wastewater.

2.1.1 Problems from Vegetable Processors

The type of vegetable processed would determine the characteristics of the wastewater. For example, with tomato and carrot processors, the pH of the wastewater could dip below 4.5 (Lehto et al., 2009), which would be in violation with municipal sanitary sewer discharge limits. Table 1 will outline some of the most common problems with vegetable wastewater.

<table>
<thead>
<tr>
<th>Type of Wastewater</th>
<th>Problem</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Potato</td>
<td>high solids</td>
<td>Austermann-Haun et al. (1999)</td>
</tr>
<tr>
<td>Carrot</td>
<td>low pH</td>
<td>NSCEP (1977)</td>
</tr>
<tr>
<td>Carrot</td>
<td>volume of water used for cleaning</td>
<td>Kern et al. (2006)</td>
</tr>
<tr>
<td>Cassava</td>
<td>contains cyanide (3.5 mg/L)</td>
<td>Colin et al. (2007)</td>
</tr>
</tbody>
</table>

Even though many different problems arise during the processing of fruits and vegetables, the most common surcharge would still be based on the BOD$_5$ and TSS concentration. However, municipalities are also discussing the possibility of decreasing the allowable limits for TKN and TP or enforcing the surcharge more stringently. Chemical oxygen demand test will be used in place of the BOD$_5$ test for the quicker and more reliable results (Bullock et al., 1996). The value
of COD will always be greater than that of BOD\textsubscript{5}, which is safe to assume that if the surcharge limitations for BOD\textsubscript{5} are met with the COD tests, then the BOD\textsubscript{5} limit should also be within limits as well. The benefits to using COD as opposed to BOD\textsubscript{5} when testing wastewater is that results can be obtain more rapidly. However, it is not possible to determine a definite ratio between the two values. COD will be used during regular testing and BOD\textsubscript{5} will be used to confirm that the COD is indeed larger than BOD\textsubscript{5}. The focus of the research will be based on the organic loading and nutrient removal of TKN and TP.

From the problems that arise through various vegetable processors, as seen from Table 1, it is difficult to determine a single technology that could treat all types and characteristics of vegetable processing wastewater. Therefore, further research is required to determine the suitable technology based on the vegetable processing wastewater collected from Industrial Partner 1 and 2.

2.1.2 Effect of Nutrients on the Environment

Biochemical oxygen demand (BOD\textsubscript{5}) is the amount of oxygen that is required by the microorganisms present in the water for growth. If the oxygen used for microbial growth is high, this would indicate that the BOD\textsubscript{5} is high, which would mean that less oxygen is available for larger organisms such as fish and plants. Chemical oxygen demand is the equivalent measure of the amount of oxygen used when compared to the amount that is required to oxidize organic matter (Zhou, 2012).

Nitrogen is mainly responsible for eutrophication that occurs within oceans whereas phosphorus is mainly responsible for eutrophication that occurs in lakes (Correll, 1998; Randall et al., 1998).
Phosphorus binds through sediments, which is then transferred into lakes and reservoirs. The nutrients would promote the growth of algae, which in turn would leave the water body with less than normal oxygen levels. The boom in algae growth usually occurs during the spring runoff from the nearby land. Combined with an increase in temperature which then lowers the natural solubility conditions of oxygen, there would be a lower concentration of dissolved oxygen through the oxygen depletion by the algae boom. After the death of the algae, the biomass sinks to the bottom of the lake, which creates anaerobic zones. If sunlight was to be able to reach to the spots, then this would be enough to revive the system to be aerobic, but because generally this process creates murky water, sunlight is unable to reach to the bottom.

2.1.3 Municipal By-laws

The most effective way for preventing an excessive amount of nutrients from entering into waterways is to impose a limitation and surcharge that is acceptable for discharge. Currently, there are no province wide or nationwide regulations as this involves municipal regulation. The discharge of organic loading and nutrients also does not require a certificate of authorization from the various municipalities.

Table 2 outlines the discharge limits that are allowed for sanitary sewers and Table 3 outlines the allowable limits for storm sewers.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>BOD₅ (mg/L)</td>
<td>300</td>
<td>300</td>
<td>300</td>
</tr>
<tr>
<td>TSS (mg/L)</td>
<td>350</td>
<td>350</td>
<td>350</td>
</tr>
<tr>
<td>TKN (mg/L)</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>TP (mg/L)</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>pH</td>
<td>&lt; 6 and &gt; 11.5</td>
<td>&lt; 5.5 and &gt; 10</td>
<td>&lt; 4.5 and &gt; 9.5</td>
</tr>
</tbody>
</table>
TKN is typically chosen as the indicator for nitrogen as opposed to total nitrogen because TKN indicates the concentration of organic and ammonia nitrogen within the sample. The value of COD will be taken in replacement of BOD$_5$, due to the shorter time required for the test. The concentration of COD will always be greater than BOD$_5$, so therefore, it is safe to make this assumption. However, BOD$_5$ testing for several samples will also be done to ensure that the assumption holds true.

The majority of municipalities impose a charge for discharge into the sewer system when concentrations are above the given limit. The surcharge is based on both the concentration of the nutrients within the wastewater and the flow that it is discharged at. Depending on the municipality, surcharge limits are calculated slightly different. For Toronto, the surcharge is based on the highest exceedance level between BOD$_5$ or TSS and is charged with a flat rate of $0.57$/kg. For Mississauga, that is part of The Region of Peel, the rate is $328/1000$ m$^3$ (Ravindran, 2014), however, TKN is not currently charged. For Guelph, it is based on the surcharged parameter (City of Toronto, 2012).

### 2.1.4 Solids and Nutrients Removal

This sub-section will outline the mechanisms involved when removing organic loading and nutrients from the vegetable processing wastewater.
2.1.4.1 Total Solids

Total solids and total suspended solids (TSS) can be removed through many various means. However, the general methods could consist of an addition of a chemical aid, such as a coagulant or a flocculant, the subsequent formation of flocs through excessive aeration, and through membrane filtration.

2.1.4.2 Chemical or Biological Oxygen Demand

The chemical or biological oxygen demand (Hach et al., 1997; USEPA, 2012) is used as an indicator for how much demand of oxygen is wanted within the water. The reduction of COD or BOD₅ is dependent on the water treatment process.

2.1.4.3 Total Kjeldahl Nitrogen

Nitrogen removal is achieved by the nitrification and denitrification process. Total Kjeldahl nitrogen consists of all organic forms of nitrogen, such as ammonia and ammonium except for oxidized nitrogen (PDEP, 1998). Nitrification is the process when ammonia is converted to nitrite and then subsequently to nitrate. When microorganisms acquire a carbon source for synthesis, the demand for ammonium or ammonia ions are created. The ammonium would then be oxidized to nitrite and then further oxidized to nitrate. The following equations outline the most basic form of nitrification.

\[ \text{Equation 1: } \text{NH}_4^+ + 1.5\text{O}_2 \rightarrow 2\text{H}^+ + \text{H}_2\text{O} + \text{NO}_2^- + 58 \text{ to } 84 \text{ kcal} \]  
\[ \text{Equation 2: } \text{NO}_2^- + 0.5\text{O}_2 \rightarrow \text{NO}_3^- + 15.4 \text{ to } 20.9 \text{ kcal} \]

The most basic transformation of ammonium to nitrite and from nitrite to nitrate is outlined in Equations 1 and 2 (Sharma and Ahler, 1977). Equation 1 is the conversion from ammonia to nitrite and Equation 2 is the conversion from nitrite to nitrate. The energy that is produced from
both of the equations is used by the microorganisms for growth. The two main types of microorganisms that are responsible for nitrogen removal would be the Nitrosomonas and Nitrobacter (Sharma and Ahler, 1977). Equation 1 occurs when Nitrosomonas converts the ammonia to nitrite and Nitrobacter further converts the nitrite to nitrate (Eckenfelder, 1970). Nitrification is desired because ammonia is more toxic to the environment as opposed to the final product of nitrate.

Denitrification is the conversion of nitrite or nitrate into a gaseous state, such as nitrogen gas. The conversion to nitrogen gas is desired because it is an inert gas. However, it may also be possible to form other by products, such as dinitrogen oxide, which is a greenhouse gas (Zeng et al., 2003).

The following equations outline the conversion of nitrate to nitrogen gas.

\[
6NO_3^- + 2CH_3OH \rightarrow 6NO_2^- + 2CO_2 + 4H_2O \quad (3)
\]
\[
6NO_2^- + 3CH_3OH \rightarrow 3N_2 + 3CO_2 + 3H_2O + 6OH^- \quad (4)
\]
\[
6NO_3^- + 5CH_3OH \rightarrow 5CO_2 + 7H_2O + 3N_2 + 6OH^- \quad (5)
\]

Equations 3 to 5 outline the most basic conversion between nitrite and nitrate to nitrogen gas. The equations do not include the methanol that is required for biomass growth. Equation 3 outlines the conversion of nitrate to nitrite with methanol (Metcalf and Eddy, 1972). Equation 4 outlines the conversion of nitrite to nitrogen gas with methanol (Metcalf and Eddy, 1972). Finally, Equation 5 outlines the overall reaction conversion between nitrate to nitrogen gas with the addition of methanol (Metcalf and Eddy, 1972).
The removal of BOD₅ occurs in both the aeration and anoxic stages. The aeration step would include the biomass breaking down the sBOD and using the remains as the energy and carbon sources. During the anoxic step the sBOD is used as the substrate to convert nitrite and nitrate to nitrogen gas (Gerardi, 2002a).

2.1.4.4 Total Phosphorus

Phosphorus removal can be achieved with two different methods. One method would involve the use of a chemical to removal the phosphorus, whereas the second type is the use of microorganisms. For the chemical method, it would involve a chemical precipitation process (Morse et al., 1998), where the phosphorus is adsorbed onto the surface of the adsorbent, such as alum or ferric chloride. Flocs would grow to a certain size and is then removed from the reactor. Removal by precipitation in the form of struvite is another well known process. Struvite is the chemical bonding of magnesium, ammonium, phosphate and water (Doyle et al., 2002). A well known process that would induce the formation of struvite is phosnix (Jaffer et al., 2002). However, once in the form of struvite it would be difficult to separate the phosphorus from the compound after.

Another reason as to why chemical precipitation would not be a favored choice to remove phosphorus would be the concentration of the ions that would be present within the system. To induce chemical precipitation, a salt would be added to the solution. The anion, which is typically chloride, would stay in the solution, which would then cause an increase in salinity (Loosdrecht et al., 1997). Further, it is not possible to recover the phosphorus that had been adsorbed onto the adsorbent.
The second type of removal relies on the growth of the microbial biomass. Phosphorus removal by biological process (Stratful et al., 1999) or more commonly known as EPR (enhanced phosphorus removal) can be broken down into two major reactions; anaerobic and aerobic. When the bulk liquid was aerated, it was found that the microorganisms were able to uptake the phosphorus from the liquid. On the other hand, when it was not aerated, phosphorus was released. However, it was also found that excessive aeration would promote phosphorus being released in the anaerobic stage, which suggested that the microorganisms would prefer to use oxygen rather than phosphorus for growth (Marais et al., 1987).

During the anaerobic stage, the microorganisms would use the poly-phosphate (poly-P) as the energy source to form adenosine triphosphate (ATP). At this time the microbial biomass would also be releasing orthophosphate into the liquid. ATP then reacts with volatile fatty acids (VFA) to form poly(hydroxylalkanoates) PHA. PHA is then used as the energy source to allow for the microorganisms to grow. The biomass would then take in the orthophosphate that was previously released into the liquid as an energy source, thus, removing the phosphorus from a sample.

Since soluble COD also contributes to the amount of VFA present, this would inadvertently be another source of COD removal as well.

### 2.2 Available Technology

Table 4 outlines some of the technologies which are currently used for the reclamation of vegetable processing wastewater. Figure 1 outlines some of the common technologies which are readily available. Even with a vast amount of technologies available, it is still difficult to
determine the technology that is best suited for a specific type and concentration range of vegetable processing wastewater. However, for high strength wastewater, anaerobic treatments are more typically used. Since the study of this type of wastewater is still new, further research is required to determine the most suitable technology that could be used to treat it.
Table 4 – COD Removal Efficiencies of Various Technologies

<table>
<thead>
<tr>
<th>Type of Wastewater</th>
<th>Technology</th>
<th>Initial (mg/L)</th>
<th>Removal Efficiency (%)</th>
<th>Final (mg/L)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tomato Processing</td>
<td>UASB</td>
<td>4000 to 10000</td>
<td>86.6</td>
<td>536 to 1340</td>
<td>Gohill et al. (2006)</td>
</tr>
<tr>
<td>Carrot and Potato</td>
<td>UASB</td>
<td>12000 to 16000</td>
<td>&gt; 80</td>
<td>2400 to 3200</td>
<td>Rintala et al. (1997)</td>
</tr>
<tr>
<td>Carrot and Potato</td>
<td>UASB</td>
<td>9500 to 27600</td>
<td>&gt; 87</td>
<td>1235 to 3588</td>
<td>Lepisto et al. (1997)</td>
</tr>
<tr>
<td>Potato Leachate</td>
<td>UASB</td>
<td>19800 to 20800</td>
<td>87.8 to 96.2</td>
<td>790 to 2416</td>
<td>Parawira et al. (2006)</td>
</tr>
<tr>
<td>Potato Leachate</td>
<td>APB</td>
<td>19800 to 20800</td>
<td>86.8 to 95.2</td>
<td>998 to 2614</td>
<td>Parawira et al. (2006)</td>
</tr>
<tr>
<td>Potato Leachate</td>
<td>APB</td>
<td>20400 to 20900</td>
<td>90 to 93</td>
<td>1463 to 2040</td>
<td>Mshandete et al. (2004)</td>
</tr>
<tr>
<td>Flour, Vegetables</td>
<td>AMBR</td>
<td>2000 to 15 000</td>
<td>81.3 to 94.2</td>
<td>374 to 870</td>
<td>He et al. (2005)</td>
</tr>
<tr>
<td>Agricultural</td>
<td>Wetland</td>
<td>1006</td>
<td>73.1</td>
<td>270.6</td>
<td>Sun et al. (1998)</td>
</tr>
<tr>
<td>Various Vegetables</td>
<td>UF</td>
<td>2280</td>
<td>60.5</td>
<td>900</td>
<td>Reimann (2002)</td>
</tr>
<tr>
<td>Potato Processing</td>
<td>UASB</td>
<td>4500</td>
<td>79.5</td>
<td>922</td>
<td>Zoutberg and Eker (1999)</td>
</tr>
<tr>
<td>Potato-Starch</td>
<td>AN-AO</td>
<td>16000 to 18000</td>
<td>68.8 to 72.2</td>
<td>5000 to 10000</td>
<td>Abeling and Seyfried (1993)</td>
</tr>
<tr>
<td>Vegetable Oil</td>
<td>UF</td>
<td>550</td>
<td>90.9</td>
<td>50</td>
<td>Mohammadi and Esmaeelifar (2004)</td>
</tr>
<tr>
<td>Vegetable Oil</td>
<td>Electrocoagulation</td>
<td>15000</td>
<td>98.9</td>
<td>165</td>
<td>Un et al. (2009)</td>
</tr>
<tr>
<td>Carrot Wash</td>
<td>Wetland</td>
<td>161</td>
<td>34.65</td>
<td>105.2</td>
<td>Kern et al. (2006)</td>
</tr>
</tbody>
</table>
Figure 1 – Types of Technologies Available for Different Wastewater
2.2.1 Chemical

A chemical process would change the characteristics of the wastewater to promote the settleability or structure of the compounds within the water itself. A chemical aid would include compounds that would be considered as a coagulant or processes such as electrocoagulation.

2.2.2 Physical

Physical process would be one where there is no change to the properties of the compound that is being removed from the wastewater. As such, physical processes could include the use of filtration, membranes, natural settling or adsorption.

2.2.3 Biological

The biological processes require microorganisms to degrade the nutrients within the wastewater to compounds which are less toxic to the environment. Biological processes can be split into aerobic and anaerobic. Both processes are able to remove a wide range of nutrients, however, anaerobic processes are capable of removing greater nutrient contents. The following section outlines some typical technologies which are capable of removing organics and nutrients.

2.2.3.1 Upflow Anaerobic Sludge Blanket

The upflow anaerobic sludge blanket (UASB) is a type of reactor that allows for a continuous process (Lettinga and Hulshoff Pol, 1991). Wastewater would enter through the bottom of the reactor and would flow in an upward fashion until it reaches the top. The reactor itself is mainly filled with biomass or sludge. The properties of the sludge itself would prevent it from leaving the reactor (Gohil et al., 2006). There is also a cone at the top of the reactor to collect methane gas, but is also used to prevent the uprising flocs of biomass from leaving the system (Selvamuraugan et al., 2012). This process is a continuous process, which means that it would
require a constant flow to enter and leave the system, which could potentially be a problem if the process is not continuous. Further, there is also a long acclimation period that is required when using the UASB. Even though the UASB could reduce organic and nutrient concentrations to be below the sanitary sewer discharge limit, it still requires a secondary process to achieve the storm sewer discharge limit (Gohil et al., 2006).

2.2.3.2 Membrane Bioreactor (MBR)

There are two main flow structures that are possible for membrane filtration. It would be possible to either have a cross flow or submerged hollow fibre membrane filtration. With the application for wastewater treatment, the more common type would be hollow fibre membrane filtration. Suction pressure is applied on either end or both end of the fibre, promoting the wastewater to permeate from outside to inside the membrane. The membrane itself is covered with pores with a normal pore size of a few nanometers, typically to be 0.3 micrometer. It would be possible to achieve high organic removal efficiency with this technology, but it also requires high maintenance costs. Additionally, the control of the fouling that occurs must also be monitored more carefully. Membranes are also useful when space is a limiting factor (He et al., 2005). Further, membranes could also be coupled with other technologies, such as the SBR to create a membrane sequencing batch reactor (MSBR) (Tu et al., 2010).

2.2.3.3 Anaerobic Packed Bed

Another type of technology that is used to treat vegetable processing wastewater would be the anaerobic mixed biofilm reactor (Romano and Zhang, 2008) or anaerobic packed bed (APB). Instead of having free sludge settle at the bottom of the reactor, the biofilm reactor would allow for microbial growth on the surface of the packing material (Ødegaard et al., 1994). Since the microbial growth is on the surface of the packing material, the chances of washout are lower than
in suspended situations. Further, with this process, no backwash is needed (Ødegaard et al., 1994).

2.2.3.4 Anaerobic Sequencing Batch Reactor

The anaerobic sequencing batch reactor (ASBR) is governed by 4 main processes, feed, react, settle and decant (Dague et al., 1992). The removal efficiency of the ASBR is determined by the food and biomass ratio (Dague et al., 1992). The lower the ratio, the more easily flocculation would occur. Like the other anaerobic processes, the ASBR is able to collect energy from the production of biogas as well (Suthaker et al., 1991).

2.3 Aerobic Sequencing Batch Reactor

Even though there are many different technologies made available to reclaim vegetable processing wastewater, there is limited research on the use of a sequencing batch reactor on the reclamation of vegetable processing wastewater. The characteristics of vegetable processing wastewater could vary greatly. The characteristics of the wastewater are highly dependent on the type of vegetable that the facility is processing. Therefore, it was decided that a SBR would be a suitable technology that could be used to treat vegetable wastewater since it is highly versatile and adaptive.

SBR have not been introduced to vegetable processing facilities because the regulations prior have not been stringently enforced. However, with more stringent regulations and increasing fines, an SBR could become a viable method to reduce or eliminate surcharges.
The sequencing batch reactor is similar to that of an anaerobic sequencing batch reactor. However, the difference between the two systems is that the aerobic sequencing batch reactor is aerated.

Generally, there are 5 different stages to an aerobic sequencing batch reactor, which are feed, react, settle, decant and idle. The feed stage is when the reactor is fed with its respective wastewater. The reaction period is when the SBR is either aerated or mixed. If phosphorus was the targeted nutrient for removal, then the SBR will be mixed for an allocated amount of time before aeration. Mixing of the system without oxygen is called anaerobic. Phosphorus will be released during the anaerobic time, but with an excess uptake during the aerobic zone, the phosphorus is removed. However, if only nitrogen was the targeted nutrient for removal, then the SBR will be aerated and then left to be mixed for an allocated amount of time. Mixing of a system after aeration is called anoxic. Nitrification occurs during the aerobic time, where ammonia is converted to nitrite or nitrate. Denitrification occurs during the anoxic phase, when nitrite and nitrate is further broken down to nitrogen gas. The settle phase allows for the sludge within the reactor to settle out to the bottom where it would be possible for the decant stage to remove a certain amount of liquid from the reactor. The idle phase is when the entire reactor is stationary for a determined amount of time.

Figure 2 outlines the nutrient removal process for a SBR and Figure 3 gives a general diagram of the SBR.
Figure 2 – Nutrient Removal Process for a Sequencing Batch Reactor

Figure 3 – General Configuration of a SBR

2.3.1 General Operation

Table 5 outlines some of the reported removal efficiencies of SBRs with various types of wastewater. Furthermore, Table 5 also provides evidence to the versatility of the wastewater that the sequencing batch reactor can handle. Though there have been much research on the SBR and the type of wastewater which it can reclaim, no research was found in the literature for vegetable
processing wastewater. Knowing that the SBR can reclaim many types of wastewater, it should be tested at the lab scale.
<table>
<thead>
<tr>
<th>Type of Wastewater</th>
<th>Initial Values (mg/L)</th>
<th>Removal Efficiency (%)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>COD</td>
<td>TKN</td>
<td>TP</td>
</tr>
<tr>
<td>Piggery</td>
<td>10580</td>
<td>1258</td>
<td>236</td>
</tr>
<tr>
<td>Shrimp Production</td>
<td>1555</td>
<td>146</td>
<td>N/A</td>
</tr>
<tr>
<td>Industrial</td>
<td>1900</td>
<td>185</td>
<td>45</td>
</tr>
<tr>
<td>Oil Refinery</td>
<td>4774</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Dairy</td>
<td>10000</td>
<td>780</td>
<td>N/A</td>
</tr>
<tr>
<td>Brewery</td>
<td>2853</td>
<td>200</td>
<td>N/A</td>
</tr>
<tr>
<td>Malting</td>
<td>912</td>
<td>11</td>
<td>39</td>
</tr>
<tr>
<td>Tannery</td>
<td>2106</td>
<td>185</td>
<td>N/A</td>
</tr>
<tr>
<td>Landfill and dairy</td>
<td>3500</td>
<td>800</td>
<td>N/A</td>
</tr>
<tr>
<td>Landfill and Dairy</td>
<td>7250</td>
<td>75</td>
<td>N/A</td>
</tr>
<tr>
<td>Piggery</td>
<td>2255</td>
<td>909</td>
<td>89</td>
</tr>
<tr>
<td>Pulp Mill</td>
<td>550</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Coke</td>
<td>623</td>
<td>107</td>
<td>N/A</td>
</tr>
<tr>
<td>Synthetic</td>
<td>400</td>
<td>40</td>
<td>15</td>
</tr>
</tbody>
</table>

Table 5 – Nutrient Removal Efficiency of Various SBR Systems
2.3.2 Parameters Affecting Removal Efficiency

As with any process, certain parameters will govern how a system will function. With a SBR, the most important parameters are temperature, dissolved oxygen, pH, SRT, HRT, organic loading, liquid exchange ratio and its sludge properties (Sharma and Ahler, 1977).

2.3.2.1 Temperature

Microorganisms are extremely temperature dependant, regardless of the species. Above or below a certain range, the microorganisms would not be able to survive. Therefore, it is vital that the operating temperature of the reactor is within a reasonable value of the operating range. As it could be seen from the experiments by Obaja et al. (2003), low ammonia removal was achieved at low temperatures, but even as the temperatures reach a maximum, diminishing returns was achieved. Tripathi et al. (1999) have also further demonstrated that at temperatures higher than the desired temperature would decrease the overall removal efficiency of COD. Tripathi et al. (1999) had found that with a temperature of 35°C, the average removal efficiency for COD was 75%. Increasing the temperature up to 60°C, had decreased the COD removal efficiency to 63%.

2.3.2.2 Dissolved Oxygen

As previously discussed, nitrification requires a sufficient amount of oxygen in order to convert the ammonia to nitrite and nitrate. However, it was also found that at 4 mg/L, the concentration of dissolved oxygen in the system would no longer be a limiting factor (Mulkerrins et al., 2004). The anaerobic and anoxic time on the other hand both requires that the dissolved oxygen concentration to be as close to zero as possible, in order to achieve high nutrient removal.
2.3.2.3 pH

The pH of the system would dictate the species that would exist in the solution. Anthonisen et al. (1976) reported that ammonia and free nitrous acid would both hinder microbial growth. The pH would dictate which species of the total ammonia would be present in the system, let it be ammonia or ammonium. At high pH, majority of the species present would be ammonia and at lower pH the species would be ammonium. However, at a low pH, free nitrous acid would be present and would also hinder growth. Thus, it was found that the optimal nitrification pH would be slightly towards the alkaline side, as it was discussed by Knowles (1982).

2.3.2.4 Sludge Properties

Another factor that could affect the removal efficiency would be the composition of the sludge. Generally the system could be broken down into a suspended growth or an attached growth reactor. The experiments from Ling et al. (1999) had shown that removal efficiencies for COD were generally constant with suspended growth with various HRT, while attached growth systems increases with increasing HRT. For an attached system, the microbial growth is attached onto strands throughout the reactor. The suspended system on the other hand would have the microbial biomass freely in the reactor. Suspended growth will be used in the experiments to achieve consistent results even with varying HRT. The microbial biomass growth of the system could be further broken down into granules or filamentous growth.

The difference between the two types of growth would be the settleability differences. Granule growth is more clumped together and filamentous growth is a fluffier type of growth. Since granule growth is able to settle faster, filamentous growth is generally not favored. Filamentous growth is present in all bioreactors, but a high concentration of them would generally be
unwanted. A low concentration of filamentous growth would actually stabilize the reactor (Liu and Liu, 2006). When there is a sufficient amount of filamentous growth, it was reported that it can act as a bridging agent, binding granule growth together (Gerardi, 2002b). Granule growth in the system would allow for a faster separation of solids and liquids within the reactor (Liu and Liu, 2006).

Since high concentrations of filamentous bacteria are unwanted, the parameters that promote the growth should be restricted. One of the major factors that would contribute to the growth would be the time taken for growth. Filamentous bacteria generally grow slower than granule bacteria, thus, a young sludge age would effectively reduce the concentration of filamentous bacteria (Gerardi, 2002b). A low DO concentration within the reactor would promote the formation of filamentous bacteria. It was found that a DO of 2 mg/L is required to restrict the growth (Chudoba, 1985).

Foam and scum would indicate the problems that are occurring within the reactor. As such, any scum that occurs would be an indication of a large amount of microbes dying (Gerardi, M. H., 2002b).

2.3.2.4 Hydraulic Retention Time

Another parameter of importance would be the hydraulic retention time (HRT). The hydraulic retention time is typically defined as the average amount of time that a sample resides in a system. For a batch reactor, the HRT is defined as the operation time divided by the ratio of water which leaves the system periodically divided by the total volume of the system.
The HRT is a complicated parameter that is not simply defined as acquiring a longer time would guarantee having the best removal efficiency for nutrient removal. Common belief would be similar to the study done by Klimiuk et al. (2006), where the increase in HRT between 2 to 6 days increased the BOD₅ removal efficiency from 97.5% to 99%. However, other studies, such as the one from Sirianuntapiboon and Manoonpong (2001), had found that the increase in HRT had actually caused a decrease in removal efficiency of BOD₅ between a HRT from 4 to 6 days, but then actually having the removal increased from 6 to 8 days. The HRT is not only governed by the amount of time that the wastewater resides in the system, it is also dependent on the concentration of biomass and influent nutrient concentration of the wastewater. A higher nutrient concentration in the influent but lack of biomass in the system would require a longer HRT, where the balance between the required amount of time for optimal removal will be dependent on the characteristics of the influent wastewater.

2.3.2.5 Overall General Parameters

Table 6 outlines the parameters that were used to achieve the removal efficiencies outlined in Table 5. From Table 6, the general conditions, such as temperature and DO were used for the research within this paper.
<table>
<thead>
<tr>
<th>pH</th>
<th>DO (mg/L)</th>
<th>Temperature (°C)</th>
<th>HRT (h)</th>
<th>SRT (d)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>N/A</td>
<td>N/A</td>
<td>20</td>
<td>240</td>
<td>34</td>
<td>Bartone et al. (1992)</td>
</tr>
<tr>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>Boopathy et al. (2009)</td>
</tr>
<tr>
<td>7 to 7.5</td>
<td>0.2 to 3</td>
<td>18 to 22</td>
<td>18</td>
<td>20</td>
<td>Keller et al. (1997)</td>
</tr>
<tr>
<td>7.2</td>
<td>&gt; 3</td>
<td>30</td>
<td>9.6</td>
<td>24</td>
<td>Lee et al. (2004)</td>
</tr>
<tr>
<td>8</td>
<td>&gt; 3</td>
<td>N/A</td>
<td>24</td>
<td>8</td>
<td>Li et al. (2002)</td>
</tr>
<tr>
<td>N/A</td>
<td>N/A</td>
<td>20</td>
<td>25.4</td>
<td>24</td>
<td>Ling et al. (1999)</td>
</tr>
<tr>
<td>5.8 to 6.5</td>
<td>&gt; 2.5</td>
<td>20</td>
<td>32</td>
<td>16</td>
<td>Lo et al. (1998)</td>
</tr>
<tr>
<td>N/A</td>
<td>N/A</td>
<td>7 to 30</td>
<td>71.8</td>
<td>28 to 5</td>
<td>Murat et al. (2006)</td>
</tr>
<tr>
<td>8.3</td>
<td>2</td>
<td>N/A</td>
<td>4.7</td>
<td>10</td>
<td>Neczaj et al. (2005)</td>
</tr>
<tr>
<td>N/A</td>
<td>&gt; 3</td>
<td>20</td>
<td>240</td>
<td>10</td>
<td>Neczaj et al. (2008)</td>
</tr>
<tr>
<td>8.1</td>
<td>6 to 8</td>
<td>8 to 30</td>
<td>24</td>
<td>11</td>
<td>Obaja et al. (2003)</td>
</tr>
<tr>
<td>7 to 8.5</td>
<td>&gt; 1.5</td>
<td>35 to 60</td>
<td>12</td>
<td>10</td>
<td>Tripathi et al. (1999)</td>
</tr>
<tr>
<td>N/A</td>
<td>N/A</td>
<td>20 to 28</td>
<td>48</td>
<td>40</td>
<td>Yu et al. (1997)</td>
</tr>
<tr>
<td>7 to 7.5</td>
<td>0.45 to 0.55</td>
<td>18 to 22</td>
<td>9.6</td>
<td>15</td>
<td>Zeng et al. (2003)</td>
</tr>
</tbody>
</table>
Table 7 outlines some of the more general parameters that were written in literature for optimal removal efficiency.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Temperature (°C)</th>
<th>pH</th>
<th>DO (mg/L)</th>
<th>Phases</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>20 to 30</td>
<td>7.1</td>
<td>0 to 0.2</td>
<td>Anaerobic (Mulkerrins et al., 2004)</td>
</tr>
<tr>
<td></td>
<td>28 to 36</td>
<td>7.2 to 9.5</td>
<td>3 to 4</td>
<td>Aerobic (Sharma and Ahler, 1977)</td>
</tr>
<tr>
<td></td>
<td>10 to 35</td>
<td>7 to 8</td>
<td>&lt; 0.5</td>
<td>Anoxic (Knowles, 1982)</td>
</tr>
</tbody>
</table>

The conditions outlined in Table 7 will determine the conditions that will be used for further studies.

The HRT was chosen as the varying parameter for its simple operation. The SRT would have also been another important parameter to study, however, it would have been difficult to control. In order to obtain a steady SRT, the influent wastewater must have been controlled. Further, since the SRT is dictated by the growth rate of the microbial biomass, the amount of sludge wasted per day must also had to be altered on a daily basis.

### 2.4 Disinfection

After the removal of solids and nutrients, the next step would be the application of a disinfectant. By treating the wastewater with a disinfectant and being able to achieve satisfied removal rates, it allows for the reuse of the wastewater onsite. Disinfection is the process by which microorganisms are inactivated or destroyed. The effectiveness of the disinfection process is determined by the elimination of the indicator microorganism. Typically, the indicator microorganism is chosen as one which is present within the urinary tract of warm blooded animals. The three most typical indicator microorganisms used for drinking water are, E. coli,
Cryptosporidium and Giardia. Other indicators could include B. subtilis, S. sonnei, and microflora, just to name a few (Olmelz and Kretzschmar, 2009).

Some of the more typical disinfection processes include the application of chlorine, UV, advanced oxidation processes (AOP) and organic acids. The following sections will briefly outline the uses for the various processes and its advantages and disadvantages.

2.4.1 Chlorine Disinfection

Chlorine disinfection consists of free and bonded chlorine. Free chlorine is generally used to disinfect the water, whereas bonded chlorine is used to prevent microbial growth from regrowing. Free chlorine are species that exist in water in the form of Cl\(^-\), HOCl and OCl\(^-\). Bonded chlorine are species such as chloramine and chlorine dioxide. Chlorine is the most effective against bacteria and least with protozoans. Benefits of using chlorine would include the residual left within the water. Chlorine disinfection operates by the replacement of one or more hydrogen atoms along the wall of the cell structure. With the alteration, the structure of the wall will not be able to function correctly and fail. The effectiveness of chlorine on individual indicator organisms could be observed with the required CT (concentration time). The concentration time is dependent on both the log removal and temperature. A higher temperature would generally require a shorter CT value.

The CT value is calculated as the chemical dosage multiplied by the time required for the inactivation of the microbes. Other than using the designed contact time, it would also be possible to track the amount of microbial activity at the end of the dosing. Since microbial
growth would typically take days, it would not be possible to have a continuous monitoring process.

The major shortcoming of chlorine disinfection is the by-products that could be formed. It is possible with chlorine disinfection that trihalomethanes (TTHM) could be formed. TTHM are formed when chlorine is used to disinfect water that contains natural organic matter (Singer, 1994). Currently the standard for cities that contains a population larger than 10 000 would be less than 0.08 mg/L (USEPA, 2010). Further, the chlorine required will need to be transported on site, as opposed to created on site, thus increasing the cost of the system. Chlorine also provides an undesirable taste (Kerwick et al., 2005).

2.4.2 Advanced Oxidation

Other processes that are made available would be classified as advanced oxidation processes. The theory behind the use of an oxidant is similar to that of the addition of chlorine. The oxidant will disrupt the protein structure of the cell, thus causing it to fail. Advanced oxidation process could include ozonation and other various combined treatments. One of the more common practises would be the cleaving of hydrogen peroxide ions into radical hydroxide ions (Zhou et al., 2002). Advantage of this technology would include the on-site production of ozone, thus reducing transportation costs of the chemical.

Production of ozone on site could reduce transportation fee, however, it is extremely corrosive and requires additional maintenance to keep production level of ozone above the minimum requirement (USEPA, 1999a). The functions are similar to that of chlorine but does not promote the formation of TTHM and other disinfection by-products which are hazardous compounds.
Although advanced oxidation also does not provide a residual disinfectant. Thereby, it may be possible to have contamination occurring prior to delivery to the home. Studies have shown that a high concentration of ozone could also degrade vegetables (Olmez and Kretzschmar, 2009).

### 2.4.3 Ultraviolet Disinfection

UV disinfection is the use of halogen lamps with wavelengths between 200 to 280 nm (Koutchma et al., 2009), to inactivate the micrograms. The wavelengths of the light disrupts the natural DNA sequencing, thus, making them unable to replicate further. The microorganisms are not destroyed, but are simply hindered for further replication. UV disinfection is the least effective against viruses (Hijnen et al., 2006). However, it was found recently that endospores is more difficult to destroy than viruses when applying UV disinfection (Chevrefils et al., 2006). There is no further addition of chemicals into the system so no by-products are formed.

UV disinfection could be carried out in a single lamp orientation or with multiple lamps. For a multiple lamp system, the lamps could be staggered throughout the system, which could create various flow patterns. The dosage required for the UV disinfection is similar to that of chlorine disinfection. Both uses the CT value to determine the dosage required. However, with chlorine, the contact time could be within the units of minutes, UV would only require several seconds (USEPA, 1999b).

Although there are many benefits for the usage of a UV system, one of the main concerns is the lack of residual disinfectant within the water as it leaves the system. Without a residual, it could be possible for contamination prior to that being delivered. Furthermore, fouling of the lamps is
also a primary concern. The delivery dose is based on both the contact time and the dosage applied. When fouling occurs on the surface of the lamp, the applied dosage is minimized, thus, an increased contact time is required. Furthermore, the flow paths of water around multiple lamp system could also have an effect on the applied dosage as well. Water which takes a faster path would have a lower contact time (Wright et al., 2006). The turbidity of the water would also affect the dosage applied to the water as well.

For the testing of the effectiveness of UV disinfection, a collimated beam is typically used within the laboratory scale. The purpose of the collimated beam is to apply perpendicular light onto a sample evenly. As such, the configuration could be seen in the following diagram.

![Light Funnel Sample](image)

**Figure 4 – General Collimated Beam**

Low pressure lamps can only apply a single wavelength of 254 nm, but medium pressure lamps are able to apply a broad range between 200 to 280 nm. To ensure that a collimated beam is
effective, the irradiation that is applied must be suffice. The irradiation must take into
consideration of the medium in which it is passing through, the distance between that and the
lamp itself, the material that holds the sample and others.

2.4.4 Other Methods

Other methods which are available for water disinfection are electrochemical, cavitation and the
use of organic acids, just to name a few.

2.4.4.1 Electrochemical

Electrochemical water disinfection is the use of electrical current to disinfect water (Martinez-
Huitle and Brillas, 2008; Patermarkakis and Fountoukidis, 1990). By having two metal plates
inserted into the water sample and applying a current through the water, disinfecting species,
such as hypochlorite, will be created (Kraft, 2008). Depending on the chemical species that is
formed, the same principles for disinfection would then be applied. Since electrochemical can
produce both various chlorine species and oxidation species as well, the benefits and downfalls
are also the same.

The major disadvantage with electrochemical would be the fouling or depletion of the plates
required for the production of the disinfecting species (Kerwick et al., 2005).

2.4.4.2 Cavitation

Cavitation is the formation of bubbles within a liquid due to an increase in pressure difference
(Jyoti and Pandit, 2001). The pressure and change in temperature would cause cell damage
similar to that of an autoclave. Cavitation occurs when water is forced through constricted pipes.
Since it is a physical process, it will not create any unwanted by-products. However, with all the benefits of this technology, the use of cavitation does require a large amount of energy.

2.4.4.3 Organic Acids

Organic acids are acids which only contain organic compounds, such as citric and acetic acid (Olmez and Kretzschmar, 2009). The weak acid enters into the cell where it will dissociate. The lowering of pH and increase in the anions in the cell will inhibit future growth (Theron and Rykers-Lues, 2011). Organic acids are classified as one of the methods in GRAS (Generally Recognized As Safe) (Olmez and Kretzschmar, 2009).

The major shortcoming of using organic acids is the vast differences between the acid used and its dosage required for the various types of fruits and vegetables. Further, the required concentrations needed to inactivate the microorganisms could be so great that it could provide an undesirable taste to the specimen (Olmez and Kretzschmar, 2009).

2.5 Overview

Overall there is little research available on the removal technologies and the effectiveness against removing organic loading and nutrients from vegetable processing wastewater. Not only does vegetable processing wastewater create problems onsite, such as foaming problems for cassava and potato processors, they also reduce the pH (when processing carrots) of wastewater as it enters into the sanitary sewers as well, thereby creating problems onsite and offsite. When organic loading and nutrients enters into waterbodies directly, they strip away oxygen from the water, leaving an extremely low dissolved oxygen concentration for larger animals, such as fish. Therefore, there is a huge want to advance the reduction in organic loading and nutrient concentration of the wastewater prior to being discharged into the local sanitary sewer system.
Even with the USEPA (1995), there is no available research on effluent guidelines for vegetable processing wastewater even though they have specific guidelines for almost all other industries available.

To reduce the organic loading and nutrients from the wastewater prior to discharge, a removal technology is required. The SBR was chosen for its simple operation and capability of removing organic loading and nutrients from different kinds of wastewater. UV disinfection was also used for its simple operation and lack of formation of by-products. Bacillus subtilis was chosen as the testing microorganism since it is not harmful to humans, could be found within the soil environment and since it is an extremely resilient to UV disinfection.
Chapter 3: Methodology

This section will include details about the design of experiments, the standard operating procedure of the overall experiment and analysis techniques.

3.1 Collection of Vegetable Processing Wastewater

Vegetable processing wastewater was collected on a weekly basis at a facility located in the Region of Peel for Industrial Partner 1. The water that was used to process the fruits and vegetables were sent directly to a storage basin. The wastewater was collected from a storage basin prior to discharge into the local sanitary sewers. The facility currently does not have any solids or chemical treatment in place. 20 L of wastewater was collected on a weekly basis and the sampling time typically took 10 minutes. Since the storage basin was over 2 meters in height, a hand pump was used to ease the collection of the wastewater. After collection, the wastewater was transported back to the university and was stored in a walk in refrigerator with a constant temperature of 4°C.

The vegetable processing wastewater was collected at a location in the City of Toronto. After water has been used to treat and process the potatoes and carrots, the wastewater is then pumped to an open pit before being sent to treatment and discharged into the local sanitary sewer system. The collection point for Industrial Partner 2 is at the open pit and typically took about 15 minutes. Wastewater was collected on a monthly basis and transported back to the university where it was stored in a walk in refrigerator at 4°C.
3.2 Overall Design of Experiments

After much consideration it was determined that the focus of the research would be on COD, TKN and TP. COD is used as the indicator due to the short testing time, and its relationship between that and $BOD_5$. Current and future By-laws includes both TKN and TP. There is a want to decrease the allowable limits on both of these nutrients due to the eutrophication process.

Taking into consideration the major parameters that affect the removal efficiency of nutrients and organics with a SBR, it was determined that the operational temperature of the SBR will be set at room temperature at 23°C, governed by the natural heating of the lab. Further, the amount of dissolved oxygen during aeration will use a diffuser that produces 300 L/h. Qin et al. (2004) had found that aeration systems which provided 180 L/h during aeration was capable of over saturating the system. The SRT is held steady at a rate of 25 days and the MLSS concentration is found to be at 10.4 g/L during the acclimation.

It was determined that the HRT will be the aspect that will be studied. The HRT is easy to change and maintain and little research is known about the effect of HRT on the removal efficiency for vegetable processing wastewater. The operation of the system involves fill, react, settle, decant and idle. The fill, settle, decant and idle phases will be the same for all experiments, which are 15, 30, 15 and 30 minutes respectively. The react phases will be further broken down to an anaerobic and aerobic phase. It was determined by Kargi and Uygur (2004) that the time required for phosphorus removal during the anaerobic phase could be kept stationary with 120 minutes, which is what will be used for further experimentation. The
experiments will be further broken down with the amount of liquid that is drawn from the system.

Prior to imposing case conditions onto the reactor, the reactor must first be acclimatized. The acclimation period will allow the microorganisms to adapt to the wastewater that it is reclaiming. The acclimatization period should last until the removal efficiency of nutrients only deviated within 10%.

Table 8 outlines the first three experiments that will be conducted. Table 9 outlines all the conditions for the experiments. The aeration time for Experiments 1-4 through 1-6 was determined from the results of Experiments 1-1 through 1-3. The results between Experiment 1-2 and 1-3 were similar; it was determined that the aeration time used for Experiment 1-3 will be used for Experiments 1-4 through 1-6. The smaller hydraulic retention time would result in a smaller footprint the reactor.

<table>
<thead>
<tr>
<th>Exp</th>
<th>Cycle Time (h)</th>
<th>Fill (min)</th>
<th>React (min)</th>
<th>Settle (min)</th>
<th>Decant (min)</th>
<th>Idle (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Anaerobic</td>
<td>Aerobic</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1-1</td>
<td>12</td>
<td>15</td>
<td>120</td>
<td>450</td>
<td>30</td>
<td>15</td>
</tr>
<tr>
<td>1-2</td>
<td>8</td>
<td>15</td>
<td>120</td>
<td>270</td>
<td>30</td>
<td>15</td>
</tr>
<tr>
<td>1-3</td>
<td>6</td>
<td>15</td>
<td>120</td>
<td>150</td>
<td>30</td>
<td>15</td>
</tr>
</tbody>
</table>
Table 9 – Overview of Experiments

<table>
<thead>
<tr>
<th>Experiment</th>
<th>SRT (min)</th>
<th>Aerobic (min)</th>
<th>Effluent Drawn (L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-1</td>
<td>20</td>
<td>450</td>
<td>1.5</td>
</tr>
<tr>
<td>1-2</td>
<td>20</td>
<td>270</td>
<td>1.5</td>
</tr>
<tr>
<td>1-3</td>
<td>20</td>
<td>150</td>
<td>1.5</td>
</tr>
<tr>
<td>1-4</td>
<td>20</td>
<td>150</td>
<td>1</td>
</tr>
<tr>
<td>1-5</td>
<td>20</td>
<td>150</td>
<td>2</td>
</tr>
<tr>
<td>1-6</td>
<td>20</td>
<td>150</td>
<td>2.5</td>
</tr>
</tbody>
</table>

Table 10 and 11 both outlines the resulting HRT as a result of the cycle time and effluent that is drawn from the system.

Table 10 – Aeration Experiments

<table>
<thead>
<tr>
<th>Cycle Time (h)</th>
<th>Effluent Withdrawn (L)</th>
<th>Total Volume (L)</th>
<th>Ratio</th>
<th>HRT (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experiment 1-1</td>
<td>12</td>
<td>1.5</td>
<td>5</td>
<td>0.3</td>
</tr>
<tr>
<td>Experiment 1-2</td>
<td>8</td>
<td>1.5</td>
<td>5</td>
<td>0.3</td>
</tr>
<tr>
<td>Experiment 1-3</td>
<td>6</td>
<td>1.5</td>
<td>5</td>
<td>0.3</td>
</tr>
</tbody>
</table>

Table 11 – Liquid Exchange Experiments

<table>
<thead>
<tr>
<th>Cycle Time (h)</th>
<th>Effluent Withdrawn (L)</th>
<th>Total Volume (L)</th>
<th>Ratio</th>
<th>HRT (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experiment 1-4</td>
<td>6</td>
<td>1</td>
<td>5</td>
<td>0.2</td>
</tr>
<tr>
<td>Experiment 1-5</td>
<td>6</td>
<td>2</td>
<td>5</td>
<td>0.4</td>
</tr>
<tr>
<td>Experiment 1-6</td>
<td>6</td>
<td>2.5</td>
<td>5</td>
<td>0.5</td>
</tr>
</tbody>
</table>

After the initial 6 experiments, 2 conditions which resulted in the highest removal efficiency from the 6 will be used for the operation for the second industrial partner. The second set of wastewater will confirm whether or not the condition is suitable for all types of vegetable wastewater.

Ultraviolet disinfection was used as the medium for microbial disinfection for its effectiveness and versatility. B. subtilis was used as the microbe to determine the effectiveness of UV
disinfection for the vegetable wastewater. B. subtilis is a spore in nature and is the most resilient against UV disinfection. If UV disinfection is capable of reducing B. subtilis, then it should also be capable of removing other indicating organisms, such as E.coli and others as well. Furthermore, disinfection will be applied with a change in time, rather than the fluence.

3.3 Equipment

The following section outlines the equipment that is used for the running of the sequencing batch reactor, the various analysis for both the solids and nutrients and the analysis techniques that is used for the ultraviolet disinfection.

3.3.1 Sequencing Batch Reactor

Table 12, outlines all of the equipment used for the sequencing batch reactor. Figure 5 shows the actual configuration of the sequencing batch reactor. The diameter of the vessel was 4.5” or 11.43 cm with a height of 68.10 cm and made from plexiglass. The porous stone that was placed inside of the vessel was 1.9 cm in height and 10 cm in diameter.

<table>
<thead>
<tr>
<th>Description</th>
<th>Company</th>
<th>Catalogue #</th>
</tr>
</thead>
<tbody>
<tr>
<td>IKA Mixer</td>
<td>Cole-Parmer Canada Inc.</td>
<td>RK-50705-00</td>
</tr>
<tr>
<td>20 L carboy</td>
<td></td>
<td>RK-62507-20</td>
</tr>
<tr>
<td>Masterflex Variable - Speed drive pump</td>
<td></td>
<td>RK-07528-30</td>
</tr>
<tr>
<td>Masterflex L/S pump head</td>
<td></td>
<td>SI-07518-00</td>
</tr>
<tr>
<td>Septic Air Pump</td>
<td>HIBLOW - Septic Solutions</td>
<td>HIBLOW HP-60</td>
</tr>
<tr>
<td>Ozone airstone/Ozone diffuser</td>
<td>Alita Industries</td>
<td>ASD-100C</td>
</tr>
</tbody>
</table>
3.3.2 Solid and Nutrient Analysis

Table 13 includes all of the equipment used for the analysis of solids and nutrients within the wastewater and Table 14 includes all of the disposables that were used during the analysis.

Table 13 – Equipment Used for Analysis

<table>
<thead>
<tr>
<th>Description</th>
<th>Company</th>
<th>Catalogue #</th>
</tr>
</thead>
<tbody>
<tr>
<td>DRB 200</td>
<td>HACH</td>
<td>LTV082.53.42001</td>
</tr>
<tr>
<td>DR5000 UV-Vis Spectrophotometer</td>
<td></td>
<td>DR5000-03</td>
</tr>
<tr>
<td>92 mm ID ceramic funnel</td>
<td>Fisher Scientific</td>
<td>FB966F</td>
</tr>
<tr>
<td>1 L Erlenmeyer flask</td>
<td></td>
<td>5430-1L</td>
</tr>
<tr>
<td>Pump</td>
<td></td>
<td>70 5105 0471PL</td>
</tr>
<tr>
<td>Oven</td>
<td>Precision Scientific</td>
<td>Thelco 28</td>
</tr>
<tr>
<td>Analytical balance</td>
<td>Sartorius</td>
<td>CPA1245</td>
</tr>
</tbody>
</table>
### Table 14 – Disposable Equipment for Analysis

<table>
<thead>
<tr>
<th>Description</th>
<th>Company</th>
<th>Catalogue #</th>
</tr>
</thead>
<tbody>
<tr>
<td>Filter paper 9 cm diameter</td>
<td>Fisher Scientific</td>
<td>09-873G</td>
</tr>
<tr>
<td>Filter paper 4.5 cm diameter</td>
<td></td>
<td>09-873D</td>
</tr>
<tr>
<td>0.45 micron Nylon tip</td>
<td></td>
<td>09 754 45</td>
</tr>
<tr>
<td>BD Luer Lok syringe</td>
<td></td>
<td>14-823-2A</td>
</tr>
<tr>
<td>s-TKN</td>
<td>HACH</td>
<td>TNT880</td>
</tr>
<tr>
<td>UHR Total Phosphorus</td>
<td></td>
<td>TNT845</td>
</tr>
<tr>
<td>COD</td>
<td></td>
<td>TNT822</td>
</tr>
<tr>
<td>HR COD (150 tests)</td>
<td></td>
<td>TNT82206</td>
</tr>
<tr>
<td>LR Total Phosphorus</td>
<td></td>
<td>TNT843</td>
</tr>
<tr>
<td>Volatile Acids</td>
<td></td>
<td>TNT872</td>
</tr>
<tr>
<td>ULR Ammonia</td>
<td></td>
<td>TNT830</td>
</tr>
<tr>
<td>LR Nitrite</td>
<td></td>
<td>TNT839</td>
</tr>
</tbody>
</table>

### 3.3.3 Ultraviolet Disinfection

UV disinfection was conducted with the use of a collimated beam built by Trojan Technologies.
Figure 6 includes a picture for the overall general configuration of the collimated beam that were used during the UV section of the studies. The parts and configuration of the design is made by Trojan Technologies.

Table 15 – Equipment used for UV Disinfection

<table>
<thead>
<tr>
<th>Description</th>
<th>Company</th>
<th>Catalogue #</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collimated beam</td>
<td>Trojan Technologies</td>
<td></td>
</tr>
<tr>
<td>Centrifuge</td>
<td>Fisher Scientific</td>
<td>75-216-362</td>
</tr>
</tbody>
</table>

Table 16 – Disposables for UV Disinfection

<table>
<thead>
<tr>
<th>Description</th>
<th>Company</th>
<th>Catalogue #</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 mL tips</td>
<td>Fisher Scientific</td>
<td>02-707-51</td>
</tr>
<tr>
<td>Nutrient agar plates</td>
<td></td>
<td></td>
</tr>
<tr>
<td>50 mL centrifuge tubes</td>
<td>Sigma Aldrich</td>
<td>CLS431655</td>
</tr>
</tbody>
</table>
3.4 Analysis Technique

This section outlines the procedures that were followed.

3.4.1 Mixed Liquor or Total Suspended Solids

The mixed liquor suspended solids method was carried out by using an oven that is heated at 103 to 105°C, filter paper with an average porosity of 1.5 μm. For the test, a 2 mL of sample of sludge was obtained from the reactor. Filter paper was left in the oven to dry over night. To prevent moisture from reentering into the filter paper, it was left in a desiccator. Initial values of the filter paper was read using an analytical balance. The filter paper was then placed into the funnel. With the suction on, deionized water was poured into the funnel until the filter paper was completely wet. Sample volume of 2 mL was then transferred onto the filter paper with the aid of a graduated pipette. The paper was then transferred onto a tin foil and was left in the oven for at least 4 hours for heating. The filter with the tin foil was left in the desiccator to cool off. Values of the filter paper with the tin foil were then read again using the analytical balance.

The exact same process could also be used to find the initial total suspended solids of the wastewater going into the system and the solids that leave the reactor.

3.4.2 Chemical Oxygen Demand

The COD analysis (Hach, 2005) requires the digester DRB200 and the spectrophotometer DR5000. The COD analysis method used is the USEPA Reactor Digestion Method or dichromate method. Since this type of digester only had well sizes of 16 mm and 20 mm, an adaptor was bought to reduce the size to 13 mm. The digester was allowed to preheat to 150°C. After the digester is preheated to 150 °C, the sample was then prepared by adding 2 mL of sample into the TNT822 vial. The vial was then inverted several times to allow for mixing or
until the suspended solids at the bottom of the vial is no longer visible. The outside of the vial was then cleaned with Kim wipes and allowed to be inserted into the digester to allow for a digestion period of 2 hours. After 2 hours of heating, the vial was left to cool until it reached the temperature of 120°C. It was then taken out and inverted several times. After the vial finally reaches room temperature the vial was then inserted into the DR5000 spectrophotometer where the barcode was read for the testing. The spectrophotometer then gave the COD concentration in mg/L.

3.4.3 Biological Oxygen Demand

The BOD₅ experiment is split into two parts, the preparation of the solutions and the calculation of the dilutions that are required. The phosphate buffer requires 6 L of deionized water per buffer pill and requires an overnight aeration to guarantee maximum oxygen saturation. After sufficient aeration, retrieve 500 mL of the buffer solution and open a poly-Seed cap and leave it mixing for 1 hour. Ensure that no part of the gel capsule falls into the solution. After one hour of mixing, allow the solution to settle for 30 minutes. Decant the liquid into a separate beaker for use. Using two 300 mL Wheaton bottles as the buffer solution blank, fill the bottles to the top and seal it with parafilm. Using two 300 mL Wheaton bottles as poly-Seed blank, inject 4 mL of poly-Seed into the bottle and fill the bottle to the top with the buffer solution. The amount of bottles used for the actual samples and the number of replicates will rely on the user to determine the appropriate amount. Typically, one sample would contain 5 dilutions with 2 replicates each. The sample bottles would contain the required sample volume, 4 mL of poly-Seed solution and would be filled to the top with the buffer solution and sealed. An initial dissolved oxygen reading would be made prior to the sealing of the blank buffer solution bottles. Further, a reading would be made after an incubation period of 5 days at 23°C.
To ensure that the BOD$_5$ test is valid, the blanks can only deviate by 0.2 mg/L, if it is greater, then the values are not valid for those samples. A remaining concentration of DO of 1 mg/L is required and a difference of 2 mg/L from the original sample is required.

The following is the calculation required for the determination of the sample volume that is required for dilution.

With a rough estimated BOD$_5$ concentration, Equation 6 and 7 could then be used to determine the dilution range required for the BOD$_5$ test. Keeping in mind that the bottle volume is 300 mL and the minimum depletion is 2 mg/L and the remaining required DO is 1 mg/L, the following equations were used.

Equation 6 and Equation 7 allows for the calculation of the minimum and maximum range for the dilution.

\[
\text{Minimum} = \frac{\text{Minimum Depletion} \times \text{Bottle Volume}}{\text{BOD Estimate}} \quad (6)
\]

\[
\text{Maximum} = \frac{\text{Maximum Depletion} \times \text{Bottle Volume}}{\text{BOD Estimate}} \quad (7)
\]

Equation 8 could then be used to determine the concentration of the biological demand.

\[
\text{BOD}_5 \left( \frac{\text{mg}}{\text{L}} \right) = \frac{(D_1 - D_2) - S \times V_s}{P} \quad (8)
\]

\[D_1 = \text{Initial DO} \left( \frac{\text{mg}}{\text{L}} \right)\]

\[D_2 = \text{Final DO} \left( \frac{\text{mg}}{\text{L}} \right)\]

\[S = \text{DO uptake from polyseed solution}\]
\[ V_s = \text{Volume of sample} \]
\[ P = \text{Dilution factor} \]

### 3.4.4 Total Kjeldahl Nitrogen

The test kit of TNT880 (Hach, 2010a) is considered the s-TKN method. 1.3 mL of sample, 1.3 mL of sodium hydroxide and 1 tablet of reagent B was placed into a 20 mm diameter vial and was not mixed. After the contents have been added to the vial, it was allowed to be digested for 1 hour at 100 °C with the DRB200. After an hour, the vial was allowed to be removed from the reactor to be cooled to room temperature. After the vial had been cooled, a microcap C was added to the vial and was inverted till all the particles that was initially in the cap was dissolved. 0.5 mL of the vial was then pipetted into the vial with a red label and 0.2 mL of isopropanol was added to the red vial was inverted several times. 1 mL of undigested sample was added to the green vial along with 0.2 mL of isopropanol and was also inverted. After 15 minutes have passed, the red label vial was then inserted into the spectrophotometer for an E1 reading. After the red labelled vial was read, the green labelled vial was then inserted into the spectrophotometer for the final reading of total nitrogen, nitrate and nitrite, and total Kjeldahl nitrogen. All the values obtained were in mg/L.

### 3.4.5 Nitrite

For the determination of the nitrite concentration, the USEPA Diazotization Method (Hach, 2012a) was used within the TNT839 kit. Removing the foil from the vial, the cap was then flipped. 2 mL of sample was pipetted into the vial and inverted 10 times. The vial was then allowed to react for 10 minutes before a reading was made on the DR5000 spectrophotometer.
3.4.6 Ammonia

TNT830 (Hach, 2012b) uses the salicylate method when determining the concentration of ammonia within samples. The foil cap of the vial was removed and flipped. 5 mL of sample was then pipetted into the vial and inverted 10 times. After 15 minutes have passed form the initial inversion, the vial was then inverted again. After another 15 minutes have passed, the vial was then placed into the DR5000 spectrophotometer for the reading.

3.4.7 Total Phosphorus

TNT845 (Hach, 2012c) is equivalent to the ascorbic acid method in determination of the total phosphorus. The silver foil of the cap was removed and 0.4 mL of sample was added to the vial. The cap was then inverted and tightened onto the vial and was shaken several times till the particles in the cap were completely dissolved. The vial was then inserted into the digester at 100°C for 1 hour. The vial was then allowed to cool to room temperature after the digestion period. 0.5 mL of reagent B or mixture of ammonium molybdate, sulfuric acid and demineralized water was added to the vial. The vial was then inverted several times. After 10 minutes of settling, the vial was inverted several times again and a reading was then taken. Similarly, TNT843 uses the same method, but is used when determining the concentration of phosphorus at a lower concentration.

3.4.8 Volatile Acids

TNT872 (Hach, 2010b) uses the esterification method to determine the concentration of volatile fatty acids that resides in a sample. DRB200 digester was allowed to reach 100°C. 0.4 mL of sulfuric acid was added into the vial along with 0.4 mL of sample and was inverted 10 times. The vial was then allowed to be heated in the digester for 10 minutes. After 10 minutes, the vial was taken out and allowed to cool to room temperature. After the vial reaches room temperature,
0.4 mL of hydroxylamine hydrochloride was then added to the vial and was then inverted 10 times. 0.4 mL of sodium hydroxide was then added to the vial and was inverted 10 times. 0.4 mL of ferric chloride was added into the vial and was inverted 10 times. The reading of the volatile acids was then made 3 minutes after the inversion of the vial.

3.4.9 Ultraviolet Disinfection

Collimated beam was turned on, along with the fan to prevent the light from overheating. After the shutter opens, leave the light on for 10 minutes to allow for stabilization. A UV sensor was placed underneath the lamp for initial reading. Measure the height from the bottom of the light down to the second notch of where the sensor is. Recalculate the dose required if different. Equation 9 was required to determine the UV fluence.

\[
\text{Log Removal} = \frac{UV \text{ Fluence}}{UV \text{ Sensitivity}}
\]  

(9)

The log removal would be a pre-determined value and the UV sensitivity \((D_{10})\) should be determined from prior literature review. After the determination of the UV fluence required, it would then be possible to determine the time required for the dosage.

The time required could be found from Equation 10.

\[
\text{Germicidal Irradiance} \times 60 \times \text{Time (minutes)} = UV \text{ Fluence}
\]  

(10)

The central irradiance must be measured daily, but the typical value should be 0.420 mW/cm². To convert between the central irradiance to the germicidal irradiance of a low pressure UV lamp, 4 factors must first be incorporated into the measurement. The 4 factors are reflection, petri, water and divergence. These 4 factors take into account that, not the entire liquid medium will be applied a consistent dosage and that at some locations, the light may be less intense.
Reflection is the amount of light that is repelled off from the surface of the liquid or solid. The reflection factor can be calculated with Equation 11 (Bolton and Linden, 2003).

\[
\text{Reflection Factor} = 1 - R \\
R = \text{Fraction reflected}
\]

(11)

With only one lamp to apply the dosage, a petri factor is required to understand how the scattering of the light is affected with the area of the surface. The petri factor is calculated by finding the irradiance at the center and taking that value as zero. Then, by altering the position by 5 mm, the irradiance of that position is then divided by the irradiance found at position zero. The average value of the ratios will be the petri factor.

Further, since not the entire depth of a fluid sample will be consistent through the absorbance of the liquid, a water factor must be also incorporated. Equation 12 outlines the water correction factor (Bolton and Linden, 2003).

\[
\text{Water Factor} = \frac{1 - 10^{-al}}{al \ln(10)}
\]

\[
a = \text{absorbance} \left( \frac{1}{\text{cm}} \right) \\
l = \text{depth of petri dish (cm)}
\]

(12)

Lastly, a divergence factor (Bolton and Linden, 2003) is incorporated to determine how much scattering the light incurred from the light source onto the surface of the liquid.

\[
\text{Divergence Factor} = \frac{L}{L + l}
\]

\[
L = \text{length from lamp to surface of liquid (cm)}
\]

(13)
Multiplying these 4 factors (Bolton and Linden, 2003) with the central irradiance will yield the germicidal irradiance (GI) which would then be possible to calculate the time required to deliver this dosage.

\[ GI = Central\ Irradiance \times Reflection \times Petri \times Water \times Divergence \]  

(14)

3.4.10 Bacillus Subtilis Culturing

A volume of 25 to 30 mL of nutrient broth was poured into 2 centrifuge tube. A loop was used to scrape off stock culture tube. The loop was then dipped into the centrifuge tube. The tubes were incubated for 24 hours at 37°C. After the tubes became turbid, 0.5 mL of the solution was pipetted onto agar plates. The layer of liquid was spread uniformly across the plate. Upon incubating the plates further for 12 to 14 days at 30°C. After 12 to 14 days, cold sterile water was added onto the plates. The cultures were then scraped off and drained into a centrifuge tube. The centrifuge tube was then spun at 5000 rpm. The supernatant water was then decanted. Cold sterile water was added to the tube and spun at 5000 rpm. The supernatant was then decanted. This process was carried out twice more. Cold sterile water was then added into the centrifuge tube to allow for microbial suspension and then stored at 4°C.

The concentration of the B. subtilis colonies was generalized with the absorbance of the cells. Confirmation would be made with the plating of the B. subtilis colonies. Concentrated spores were diluted by 10x dilution. The first dilution would require 9 parts saline solution and one part spore. The second dilution would be 9 part saline solution and one part of the first dilution. The dilution continued till it reached 8 dilutions. Diluted solution of 5 to 8 was then poured onto different plates with 0.1 mL volume and was spread. The plates were then stored in an incubator at 30°C for 5 days. After which the plates were then counted for individual spore growth.
The concentration was calculated by counting the number of spores, dividing by the volume of liquid that was spread on the plates and then divided by the number of dilution.

### 3.5 Major Limitations

Other than requiring concentrations that are within the limits of the test kits, the following sections outlines the major limitations within each method to ensure that correct results are obtained.

#### 3.5.1 Biological Oxygen Demand

The method used for the determination of the BOD$_5$ is a concise method. However, the determination of BOD$_5$ does contain limitations. Buffer solution blanks require a depletion of no more than 0.2 mg/L of DO. A high DO depletion would indicate that there was some sort of contamination during the process. Further, a DO depletion of 2 mg/L and a final DO of 1 mg/L are required for a sample to be considered valid.

#### 3.5.2 Total Kjeldahl Nitrogen

The limitations to the s-TKN method would be the interfering substances. If COD is above 500 mg/L, then the result will be interfered. However, the combined nitrate and nitrite concentration must also be between 0.23 and 13.5 mg/L and the total nitrogen must be between 1 to 16 mg/L to ensure that readings are correct.

### 3.6 Standard Operating Procedure for the SBR

The initial set up of the reactor involved the collection of 2 L of return activated sludge from the wastewater treatment plant located within the City of Guelph. The sludge was stored in brown glass containers and was placed within a cooler for transport. After transportation, the sludge
was immediately poured into the empty SBR and vegetable processing wastewater was then further added into the chamber. The acclimation period will follow the 8 hour cycling time. The cycling time consisted of 2 hours of anaerobic mixing, 5 hours of aeration, 30 mins of settling and 30 mins of decanting. Since it is only one cycle per day, the system was then allowed to be aerated for 5 hours a night. The rest of the time was then allocated for settling. During this time, 1 L of decanted liquid was allowed to be pumped out. As well, 100 mL of sludge was removed from the reactor per day. The following steps were followed:

1. If water was already pumped out the prior day then proceed, else, pump the required amount of liquid out
2. Acquired the required amount of wastewater for the day from room THRN 1105
3. Poured the wastewater into the reactor
4. Turned the mixer on for 2 hours at 800 rpm
5. Turned off and unplug mixer after the allotted time
6. Turned the dial of the timer till it says 12 AM to begin aeration
7. The timer will automatically turn off after 5 hours
8. Decanted the sludge and water using the pump
9. Rearranged the time to start aerating after an hour for aeration throughout the night

After the initial acclimation, the procedure was altered to allow for the aeration period and liquid exchange experiments. Further, 200 mL of sludge was wasted from the reactor daily.

1. Drawn the pre-determined water out from the reactor
2. Acquired the required amount of wastewater for the day from room THRN1105
3. Poured the water into the reactor
4. Turned the mixer on for 2 hours at 700 rpm
5. Brought the before and after wastewater samples to room THRN1118 for analysis

6. Turned off and unplug the mixer after the allotted time of 2 h

7. Turned the dial of the timer till it says 12 AM to begin aeration

8. Rearranged the timer to turn off after the pre-determined aeration period

9. Rearranged the timer after two hours for aeration for 5 hours throughout the night
Chapter 4: Results and Discussion

The results are broken into 4 main sections. The first section includes the acclimation, where wastewater from Industrial Partner 1 was consistently used for 2 months. The second section includes results from the 6 various experiments. The third section takes a closer look into the results from Industrial Partner 1 with Experiments 1-2 through 1-4. The fourth and final section includes results from using the wastewater from Industrial Partner 2 for treatment.

4.1 Acclimation

Following the instructions outlined in Section 3.5 for acclimation, the data was collected and configured to produce Figure 7. The corresponding data is given in Table 17 and Table 18. Table 17 contains data collected during the acclimation from day 1 to 51, while Table 18 contains data collected during acclimation from day 1 to day 62. The two tables show the difference in the quality of data before and after a toxic shock to the microbial biomass.

![Figure 7 – Removal Efficiency During Acclimation](image-url)
Review of the acclimation data in Figure 7 showed that there was steady removal during the first 30 d, suggesting that the experiments could have started earlier than after 62 days of acclimation period. The acclimation of the wastewater from Industrial Partner 1 was fed directly to the reactor and did not require any additional substrates.

### Table 17 – Day 1 to 51 of Acclimation Data

<table>
<thead>
<tr>
<th></th>
<th>COD</th>
<th>TKN</th>
<th>TP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Initial</td>
<td>1727</td>
<td>11.3</td>
<td>6.0</td>
</tr>
<tr>
<td>Final</td>
<td>177</td>
<td>2.0</td>
<td>1.8</td>
</tr>
<tr>
<td>Removal (%)</td>
<td>90.4</td>
<td>78.3</td>
<td>64.8</td>
</tr>
<tr>
<td>SD</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Initial</td>
<td>428</td>
<td>7.8</td>
<td>2.4</td>
</tr>
<tr>
<td>Final</td>
<td>121</td>
<td>0.7</td>
<td>0.5</td>
</tr>
<tr>
<td>Removal (%)</td>
<td>4.7</td>
<td>12.3</td>
<td>15.8</td>
</tr>
</tbody>
</table>

### Table 18 – Day 1 to 62 of Acclimation Data

<table>
<thead>
<tr>
<th></th>
<th>COD</th>
<th>TKN</th>
<th>TP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Initial</td>
<td>1829</td>
<td>13.3</td>
<td>6.0</td>
</tr>
<tr>
<td>Final</td>
<td>286</td>
<td>2.5</td>
<td>1.8</td>
</tr>
<tr>
<td>Removal (%)</td>
<td>86.3</td>
<td>78.2</td>
<td>64.8</td>
</tr>
<tr>
<td>SD</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Initial</td>
<td>545</td>
<td>10.3</td>
<td>2.4</td>
</tr>
<tr>
<td>Final</td>
<td>327</td>
<td>1.9</td>
<td>0.5</td>
</tr>
<tr>
<td>Removal (%)</td>
<td>13.5</td>
<td>11.74</td>
<td>15.8</td>
</tr>
</tbody>
</table>

The importance of the acclimation period is to determine when the reactor produces results which are relatively consistent. When consistent results are obtained, it would be possible to move on with actual experiments.

During the acclimation from day 1 to 51, it appears that the results are relatively consistent, and this can be confirmed with the data in Table 17 and shown in Figure 7. The COD removal for one standard deviation (SD) is at less than 5% which is below the desired 10% outlined previously. The one standard deviation would imply that all the data points gathered are within 68% range from the mean.
However, from day 54 to 62, the removal efficiency of COD begins to drop. This could be due to the increase in organic loading. From Appendix 7.1, it could be observed that the organic loading during these days are nearly doubled, which could have overloaded the microorganisms at this time. This is further enforced with the data from day 57, which after analysis, is an outlier.

Overall, the consistency of treatment results shows that the SBR system was well acclimated and ready for further experimentations.

4.1.1 Quality Control

The analytical analysis, such as COD, TKN and TP are all based off a reading from a Hach DR5000 spectrophotometer. Therefore, it is important to determine the accuracy and precision of the spectrophotometer. From the specifications (Hach, 2010c), the wavelength accuracy is within ±1 nm and the deviation of the resulting absorbance value is less than 0.5% for an absorbance value less than 2.

Wastewater theory shows that a typical COD value is greater than that of the BOD₅. With BOD₅ being the amount of oxygen that is biologically oxidized and COD is the amount of oxygen that is chemically oxidized, general findings show that a sample would typically have a higher chemical demand than a biological one (Metcalf and Eddy, 1972). From Appendix 7.2.2, the BOD₅ data obtained for March 21, 2014 for the initial influent of Industrial Partner 1 is 580 mg/L. Whereas the COD value obtained is 1300 mg/L. The BOD₅/COD ratio would be 0.44, which again would mean that using the COD value as BOD₅ as an estimate for calculations is
valid. The following table will outline some $\text{BOD}_5/\text{COD}$ ratio that would demonstrate that the assumption holds true.

<table>
<thead>
<tr>
<th>Type of Wastewater</th>
<th>$\text{BOD}_5/\text{COD}$ Ratio</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrot</td>
<td>0.1</td>
<td>Kern et al. (2006)</td>
</tr>
<tr>
<td>Slaughterhouse</td>
<td>0.63</td>
<td>Sirianuntapiboon and Manoonpong (2001)</td>
</tr>
<tr>
<td>Landfill leachate</td>
<td>0.38</td>
<td>Klimiuk and Kulikowska (2006)</td>
</tr>
<tr>
<td>Milk industry</td>
<td>0.53</td>
<td>Sirianuntapiboon et al. (2005)</td>
</tr>
<tr>
<td>Piggery</td>
<td>0.56</td>
<td>Obaja et al. (2005)</td>
</tr>
<tr>
<td>Agricultural</td>
<td>0.46</td>
<td>Sun et al. (1998)</td>
</tr>
</tbody>
</table>

Table 19 outlines the $\text{BOD}_5/\text{COD}$ ratio for various types of wastewater. This proves that regardless of the type of wastewater, the COD is typically greater than $\text{BOD}_5$ for the same sample.

**4.1.1.1 Calibration Curves**

The following tables outline the theoretical value that should be obtained with the actual value obtained during testing. Obtaining a value that is within 2% of the theoretical data will give assurance of the data that is collected during the data collection period. Tables 20 to 22 outline the calibration of COD, TKN and TP.

<table>
<thead>
<tr>
<th>Table 20 – COD Calibration</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Theoretical</td>
<td>Actual</td>
<td>% Difference</td>
<td></td>
</tr>
<tr>
<td>1000</td>
<td>992</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>202</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>101</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 21 – TKN Calibration</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Theoretical</td>
<td>Actual</td>
<td>% Difference</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>10.2</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>5.13</td>
<td>2.6</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>1.85</td>
<td>7.5</td>
<td></td>
</tr>
</tbody>
</table>
Table 22 – TP Calibration

<table>
<thead>
<tr>
<th>Theoretical</th>
<th>Actual</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>9.87</td>
<td>1.3</td>
</tr>
<tr>
<td>5</td>
<td>5.08</td>
<td>1.6</td>
</tr>
<tr>
<td>2.5</td>
<td>2.52</td>
<td>0.8</td>
</tr>
</tbody>
</table>

From Table 20 to 22, the only large variation that exists is between the data is for TKN. The testing vials that are used for TKN analysis are used multiple times. Thus, there could still be trace elements on the surface of the vial that would have caused the discrepancy. However, for COD and TP, the percent difference is fairly small, which would signify that the data obtained for those 2 tests are valid.

According to Hach (2005) for the chemical oxygen demand, the concentration should be between 736 mg/L and 764 mg/L for a confidence interval of 95% using a standard solution of 750 mg/L, giving a percent difference of 1.9%. With the COD calibration that is lower than 1%, the data collected for COD is valid. The COD calibration requires the standard solution to tested as if it was a sample. No blank samples are required from the TNT822 test.

Hach (2013) determines that a deviation of 10% of the actual value is acceptable. A percent difference of 7.5% was found during the calibration which renders the data valid. No blank samples are required with the TNT880 test.

From Hach (2012c), it was noted that with a standard solution of 50 mg/L for total phosphorus, should give a concentration between 49 mg/L and 50 mg/L giving a percent difference of 2%. The results obtained for the calibration of the DR5000 spectrophotometer gave results that are below 2%, which signify that the data collected is valid. No blank samples are required from the
TNT845 test. The accuracy and precision of the TNT845 tests are 88.6% and 0.44% respectively (Hach, 2008).

During the tests for the COD, TKN and TP, values in mg/L was read directly off the spectrophotometer and did not require a calibration curve to determine the actual values. According to Hach (2014), an acceptable standard deviation across all of the products are also found to be within 10% of the true value. Since all of the percent difference obtained with COD, TKN and TP are below 10%, the data collected are considered valid.

4.2 Industrial Partner 1

The experimental conditions were run according to Table 23, with the results were summarized in Tables 24 to 29. Each of the experiments ran had 1 week of acclimation, followed by 2 weeks of the conditions outlined in Table 23. During these periods, samples of effluent were collected on Monday, Wednesday and Friday for testing. The effluent collected became the replicates of the various experiments. The experimental conditions of the replicates were kept consistent, such as, the temperature, aeration time, liquid exchange and other factors. The composition of the influent wastewater may be slightly different but small deviations in the removal efficiency equate to the ability of the system being able to adapt quickly to various wastewater.

<table>
<thead>
<tr>
<th>Table 23 – Dates of Data collection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Day</td>
</tr>
<tr>
<td>Experiment 1-1</td>
</tr>
<tr>
<td>Experiment 1-2</td>
</tr>
<tr>
<td>Experiment 1-3</td>
</tr>
<tr>
<td>Experiment 1-4</td>
</tr>
<tr>
<td>Experiment 1-5</td>
</tr>
<tr>
<td>Experiment 1-6</td>
</tr>
</tbody>
</table>
Tables 24 to 29 outline the initial concentration of the various nutrients and the removal efficiency. The experiments for each trial were run for a minimum of two weeks, during which 4 or 5 days were selected to test for the representative removal of COD, TKN and TP.
### Table 24 – Experiment 1-1: 450 min Aeration and 1.5 L Drawn

<table>
<thead>
<tr>
<th>Date</th>
<th>Initial</th>
<th>Final</th>
<th>Removal</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>COD</td>
<td>TKN</td>
<td>TP</td>
</tr>
<tr>
<td>08/11/2013</td>
<td>1680</td>
<td>12.1</td>
<td>5.7</td>
</tr>
<tr>
<td>11/11/2013</td>
<td>1550</td>
<td>11.6</td>
<td>5.5</td>
</tr>
<tr>
<td>13/11/2013</td>
<td>1530</td>
<td>9.9</td>
<td>5.3</td>
</tr>
<tr>
<td>15/11/2013</td>
<td>1090</td>
<td>6.2</td>
<td>4.7</td>
</tr>
<tr>
<td>10/01/2014</td>
<td>2310</td>
<td>18.5</td>
<td>16.3</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard Deviation</td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

### Table 25 – Experiment 1-2: 270 min Aeration and 1.5 L Drawn

<table>
<thead>
<tr>
<th>Date</th>
<th>Initial</th>
<th>Final</th>
<th>Removal</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>COD</td>
<td>TKN</td>
<td>TP</td>
</tr>
<tr>
<td>27/11/2013</td>
<td>1910</td>
<td>29.0</td>
<td>16.4</td>
</tr>
<tr>
<td>29/11/2013</td>
<td>1880</td>
<td>21.2</td>
<td>15.7</td>
</tr>
<tr>
<td>02/12/2013</td>
<td>1860</td>
<td>23.4</td>
<td>14.6</td>
</tr>
<tr>
<td>04/12/2013</td>
<td>1660</td>
<td>22.1</td>
<td>14.4</td>
</tr>
<tr>
<td>06/12/2013</td>
<td>3080</td>
<td>29.2</td>
<td>21.8</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard Deviation</td>
<td></td>
<td></td>
<td></td>
</tr>
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</table>
Table 26 – Experiment 1-3: 150 min Aeration and 1.5 L Drawn

<table>
<thead>
<tr>
<th>Date</th>
<th>Initial</th>
<th>Final</th>
<th>Removal</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>COD</td>
<td>TKN</td>
<td>TP</td>
</tr>
<tr>
<td>22/01/2014</td>
<td>1610</td>
<td>24.4</td>
<td>6.7</td>
</tr>
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<td>24/01/2014</td>
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<tr>
<td>29/01/2014</td>
<td>2120</td>
<td>12.1</td>
<td>17.7</td>
</tr>
<tr>
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<td></td>
</tr>
<tr>
<td>Standard Deviation</td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 27 – Experiment 1-4: 150 min Aeration and 1 L Drawn

<table>
<thead>
<tr>
<th>Date</th>
<th>Initial</th>
<th>Final</th>
<th>Removal</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>COD</td>
<td>TKN</td>
<td>TP</td>
</tr>
<tr>
<td>19/02/2014</td>
<td>1360</td>
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<tr>
<td>23/02/2014</td>
<td>1330</td>
<td>8.0</td>
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<tr>
<td>24/02/2014</td>
<td>1490</td>
<td>17.8</td>
<td>4.6</td>
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<tr>
<td>26/02/2014</td>
<td>1400</td>
<td>16.6</td>
<td>4.3</td>
</tr>
<tr>
<td>28/02/2014</td>
<td>1380</td>
<td>16.2</td>
<td>4.4</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard Deviation</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 28 – Experiment 1-5: 150 min Aeration and 2 L Drawn

<table>
<thead>
<tr>
<th>Date</th>
<th>Initial</th>
<th>Final</th>
<th>Removal</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>COD</td>
<td>TKN</td>
<td>TP</td>
</tr>
<tr>
<td>12/03/2014</td>
<td>2650</td>
<td>20.3</td>
<td>21.8</td>
</tr>
<tr>
<td>14/03/2014</td>
<td>1560</td>
<td>13.0</td>
<td>8.4</td>
</tr>
<tr>
<td>17/03/2014</td>
<td>1430</td>
<td>11.6</td>
<td>7.8</td>
</tr>
<tr>
<td>19/03/2014</td>
<td>1410</td>
<td>11.6</td>
<td>7.6</td>
</tr>
<tr>
<td>21/03/2014</td>
<td>1300</td>
<td>13.5</td>
<td>4.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

Table 29 – Experiment 1-6: 150 min Aeration and 2.5 L Drawn

<table>
<thead>
<tr>
<th>Date</th>
<th>Initial</th>
<th>Final</th>
<th>Removal</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>COD</td>
<td>TKN</td>
<td>TP</td>
</tr>
<tr>
<td>02/04/2014</td>
<td>2440</td>
<td>23.0</td>
<td>7.4</td>
</tr>
<tr>
<td>04/04/2014</td>
<td>2450</td>
<td>27.8</td>
<td>9.0</td>
</tr>
<tr>
<td>07/04/2014</td>
<td>2250</td>
<td>28.8</td>
<td>8.2</td>
</tr>
<tr>
<td>08/04/2014</td>
<td>2180</td>
<td>28.7</td>
<td>8.1</td>
</tr>
<tr>
<td>09/04/2014</td>
<td>2280</td>
<td>29.4</td>
<td>8.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Further discussions on the results will be made in the specific subsections for each parameter tested in this thesis.

4.2.1 COD

Figure 8 contains the concentration of COD before and after SBR treatment and the sanitary sewer discharge limit of 300 mg/L.

![Figure 8 – Before and After COD Concentration for Experiment 1-1 to 1-6](image)

As can be seen from Experiments 1-1 through 1-4, which corresponds to days 111 to 226, the results for COD removal are fairly similar to one another. After comparing the paired t-test amongst the experiments, it was found that there is no significant difference between the values. As such, all of the first four experiments can achieve the sanitary sewer limit of 300 mg/L, thus eliminating surcharges. However, for Experiment 1-5 and 1-6, the final effluent concentration is above 300 mg/L. With no sudden spikes in the incoming COD concentration, the high effluent COD concentration could be contributed from the operation of the SBR system during the liquid exchange changes. For Experiment 1-5 and 1-6, the liquid drawn from the system daily was
changed to 2 and 2.5 L respectively. The liquid drawn from the system was increased to create a shorter HRT. The shorter the HRT, the more water the reactor can treat per day. If it was found that a shorter HRT could produce results which are equivalent to a longer HRT, then the shorter HRT would be the preferred choice. Based on the influent, the shorter HRT could have resulted in a lack of reduction due to the lack in reaction time.

Figure 9 outlines the average COD removal efficiency with a 95% confidence interval.

![Figure 9 – Average COD Removal Efficiency with 95% Confidence Interval](image)

From Figure 9 it could be seen that Experiment 1-5 and 1-6 both produce confidence intervals which are much larger than the ones seen for Experiments 1-1 to 1-4. This could imply that when the data was obtained, the reactor had not been fully acclimated to the new condition yet and was still adjusting. This could also imply that the liquid exchange has a much greater effect on the removal efficiency than the aeration time.
To produce optimal results, a proper HRT would require a balanced SRT and loading rate (Sharma and Ahler, 1977). With a greater volume of wastewater entering into the system per cycle, the loading rate would have increased, which would have resulted in a higher demand of microorganisms within the system. If the system lacks the amount of biomass required, then it could produce removal efficiencies which are not desired.

Experiment 1-3 had the highest COD removal efficiency with 96.5%. However, Experiment 1-2 also had a high COD removal efficiency at 96.2%. After comparing the 2 removal efficiency with a paired t-test, it was found that there was no statistical difference between the 2 and thus, it can be concluded both 4.5 hours and 2.5 hours of aeration is sufficient in COD removal.

4.2.2 TKN

Figure 10 represents the TKN concentration before and after SBR treatment.

![Figure 10 – Before and After TKN Concentration for Experiment 1-1 to 1-6](image-url)
The allowable sanitary discharge rate for TKN is 100 mg/L (Toronto, 2000). Therefore, even before any treatment process, it is possible for the industrial partner to directly discharge the wastewater into the sanitary sewers. However, as there may be a possibility of more stringent By-laws in the future (City of Guelph, 2009), there is also a need to reduce the concentration of the TKN to be below the storm sewer discharge limit of 1 mg/L if this option is desired.

The measure of TKN is the total nitrogen from ammonia and organic nitrogen. Ammonia occurs naturally in the environment and is not considered harmful, nor is there a max allowable concentration that is enforced (Health Canada, 2012). Nitrite and nitrate are enforced with regulations but is not considered part of the TKN. The concentrations of nitrate are set at 10 mg/L to prevent blue-baby syndrome (McKague et al., 2014). However, ammonia is converted to nitrite, which is then subsequently converted to nitrate. Both of these pathways are considered part of the nitrification process. Therefore, it is important to reduce the concentration of ammonia to prevent it from escaping into the environment where it could then be slowly converted to nitrite and nitrate.

Figure 11 outlines the average TKN removal efficiency for Experiments 1-1 through 1-6.
As it could be seen from Figure 11, the confidence intervals of all 6 experiments are similar to one another. Since the aeration for Experiments 1-3, 1-4, 1-5 and 1-6 were all consistent, it is shown that the optimal conditions between them for the removal of nitrogen is Experiment 1-3, with an aeration time of 2.5 hours and volume drawn at 1.5 L per cycle.

Komorowska-Kaufman et al. (2006) had determined that at a temperature above 15°C and with a COD/N ratio of 3 to 9, there should be an effectiveness of ammonia removal greater than 90% with an SRT of 20 days. The current research has an SRT of 20 days but a COD/N ratio that is double than that of the recommended from Komorowska-Kaufman et al. (2006). The extremely large ratio could explain part of the removal discrepancy. It is believed, that the main cause of this discrepancy is the source of the wastewater itself.

The highest TKN removal efficiency of 90.1 % comes from Experiment 1-2, with an aeration time of 4.5 hours and 1.5 L of liquid drawn from the system per cycle.
4.2.3 TP

Figure 12 outlines the TP concentration before and after the use of the SBR, with Figure 13 showing the removal efficiency and the 5% confidence level.

![Figure 12](image1.png)

**Figure 12 – Before and After TP Concentration for Experiment 1-1 to 1-6**

![Figure 13](image2.png)

**Figure 13 – Average TP Removal Efficiency with 95% Confidence Interval**
As can be seen in Figure 13, the confidence intervals for the 6 experiments are quite large, with the biggest confidence interval from Experiment 1-1 with a value of over 20%. The data from Experiment 1-5 were also omitted due to the negative data that was obtained. The negative data obtained meant that there was an excessive release of phosphorus from the biomass during the anaerobic phase within the water as opposed to the uptake that occurs during aeration.

With Experiments 1-3, 1-4, 1-5 and 1-6 having the same aeration time, it could be seen that the Experiment 1-4 has the greatest phosphorus removal for the volume drawn. This implies that the aeration period of 2.5 hours is the most suitable for 1 L of daily influent into the system.

There may have been many factors which have contributed to the lack in phosphorus removal from the system. This includes the lack of ions, volatile fatty acids and/or biomass. Xiaolian et al. (2006) determined that the higher the sCOD:N ratio resulted in a lower TP removal. Xiaolian et al. (2006) found that even with sCOD:N ratios of 9.5 to 3.5, the resulting removal efficiency for TP increased from 47% to 94%. Comparison of the sCOD:N ratios in the completed experiments showed that they ranged from 20 to 170, which suggests that these sCOD:N ratio are too great for sufficient TP removal. Unfortunately, the sCOD:N ratio for all the experiments conducted were too sporadic, making it impossible to say with absolute certainty that exact cause. Further research is required to determine the effect of sCOD:N ratio for TP removal for the wastewater studied.

Overall, it is difficult to determine the single parameter that is responsible for the poor TP removal observed throughout the various experiments. If it was due to the lack of required
cation species within the wastewater, then the addition of magnesium and potassium (Mulkerrins et al., 2004) would increase the phosphorus removal. Additionally, the food to mass ratio should also be studied, which can be difficult.

4.2.4 General Results

The following section outlines the general results obtained when making the comparison between the 6 different experimental conditions.

Figure 14 further outlines the general removal efficiencies of all 6 experiments. The removal differences between the first 3 experiments, which represent the aeration experiments, do not vary greatly. For Experiments 1-4 to 1-6, the difference between the COD removal efficiency changes drastically. This could imply that a change in volume of liquid drawn from the reactor has a greater effect on the organic and nutrient loading than the applied aeration.

![Figure 14 – Average Removal Efficiencies for Experiments 1-1 through 1-6](image-url)
According to Figure 14, the data gathered from Experiments 1-1 to 1-6 shows that the SBR is responding as expected, when comparing the removal efficiencies to that outlined in Table 5. Keller et al. (1997) had initial COD, TKN and TP concentrations of 1900 mg/L, 185 mg/L and 45 mg/L respectively and obtained removals of 94.5%, 90.3% and 77.8%, which are similar to the results obtained with Experiments 1-1 to 1-3. However, even though it is also possible to achieve the limits for discharge into the sanitary system for COD and TKN, the high removal of TP is not as expected. As seen in Table 28, the removal values of TP are negative, which could only mean that there is an excessive production of phosphorus and not enough uptake.

For some of the results, a small standard deviation is reported, which shows that the results are very consistent. Experiments 1-1 through 1-4 are good examples for COD as the standard deviation is below 1%. On the contrary, the values obtained for TP removal yield large SD for all the experiments. The large differences within the TP removal were previously discussed in Section 4.2.3.

The highest TP removal efficiency is from Experiment 1-1 with 80.7% and the second highest is from Experiment 1-4 with 74.5%. Experiment 1-1 has conditions of 7.5 h of aeration and 1.5 L of liquid drawn, while Experiment 1-4 has the conditions of 2.5 h of aeration and 1 L drawn. This could imply that either a longer aeration period is required for TP removal or the concentration of biomass is lacking from within the reactor. Thus, having a smaller amount of phosphorus within the water would reduce the strain on the cultures within the medium.
The following table outlines the removal efficiency of COD, TKN and TP of the various experiments.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>HRT</th>
<th>COD</th>
<th>TKN</th>
<th>TP</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-1</td>
<td>40</td>
<td>95</td>
<td>80</td>
<td>70</td>
</tr>
<tr>
<td>1-2</td>
<td>26.7</td>
<td>96.2</td>
<td>90.1</td>
<td>47.1</td>
</tr>
<tr>
<td>1-3</td>
<td>20</td>
<td>96.5</td>
<td>88.6</td>
<td>46.9</td>
</tr>
<tr>
<td>1-4</td>
<td>30</td>
<td>95</td>
<td>78.5</td>
<td>74.5</td>
</tr>
<tr>
<td>1-5</td>
<td>15</td>
<td>28.9</td>
<td>63.3</td>
<td>N/A</td>
</tr>
<tr>
<td>1-6</td>
<td>12</td>
<td>39.4</td>
<td>74.2</td>
<td>48.5</td>
</tr>
</tbody>
</table>

From the results outlined in Table 30, it would appear that the ideal condition for Industrial Partner 1 would be from Experiment 1-3, which is 2.5 h of aeration with 1.5 L drawn from the reactor, due to its highest COD and second highest TKN removal efficiencies. The second overall condition would be from Experiment 1-2, which is 4.5 h of aeration with 1.5 L drawn from the reactor. The selection of the two conditions is based off the highest removal efficiencies for COD and TKN removal. Thus, the conditions from Experiments 1-2 and 1-3 will be applied to Industrial Partner 2.

To determine the ideal condition for nutrient and organic loading removal, the location of the facility must be kept in mind as this factor will determine the amount and type of surcharge the facility would incur. Since Industrial Partner 1 is located within the Region of Peel, the two most important parameters are COD and TP removal, as TKN is not regulated. Furthermore, since the surcharge cost between the various parameters are constant at $328/1000 m^3, the reduction of COD should be of the most importance, due to its initial concentration being the highest. Therefore, the ideal treatment conditions would be Experiment 1-4, due to its aeration
time of 2.5 h and 1 L of liquid exchange and the ability to remove high levels of COD at 95.0% and TP at 74.5%.

### 4.2.4.1 Effect of Aeration Time on Removal Efficiency

Figure 15 shows the relationship between the hydraulic retention time and its effect on the removal efficiency of COD, TKN and TP.

![Figure 15](image)

**Figure 15 – Effect of Aeration on the Removal Efficiency**

From Figure 15, it could be seen that the change in HRT from aeration, had little to no effect on the removal efficiency of COD. The effect of aeration on TKN removal also seems minimal, with TKN removal dropping to 80% with a HRT of 40 h. However, there does appear to be an increase in TP removal with a much longer HRT. The HRT of 40 hours corresponded to Experiment 1-1, according to Table 23.

### 4.2.4.2 Effect of Liquid Exchange on Removal Efficiency

The effect of the liquid drawn from the system per cycle is outlined in Figure 16.
Figure 16 – Effect of the Liquid Drawn on the Removal Efficiency

From Figure 16, it appears that the COD removal is greatly affected by the HRT. The HRT of 20 and 30 hours yielded removal efficiencies greater than 90%, whereas a HRT of 12 and 15 hours yielded results of 40% and 30% respectively. Further, the results for TKN removal efficiency had also fluctuated and peaking at 88.6% with an HRT of 20 h. The removal efficiency also improved with longer HRT. The TP removal reached 74.5% with an HRT of 30 h.

Thus, with the results obtained from Figure 15 and Figure 16, it appears that the volume drawn per cycle had a greater effect on the removal efficiency than the aeration period. Further, it appears that greater removal of TP occurs with longer HRT.

To be more confident in the obtained results, longer experimental times should have been allocated for each experiment. As such, more effluent wastewater samples should also be collected and tested for. The larger the number of samples the more confidence the data instills.
4.3 Specific Results for Industrial Partner 1

The following section will outline the removal rates for COD, TKN and TP for Experiments 1-2 through 1-4. These three experiments were chosen to highlight the possibility of the use of SBR treatment for the reclamation of the vegetable processing wastewater. The sanitary sewer discharge limits are also included in the figures.

These three experiments were chosen for the reasonable cycle time and overall removal efficiency.

4.3.1 Experiment 1-2

The condition for Experiment 1-2 is a cycle time of 8 hours with 4.5 hours of aeration and 1.5 L of liquid drawn from the system.

Figure 17 to Figure 19 outlines the initial, final and current sanitary sewer discharge limits of COD, TKN and TP.
Comparing the sanitary sewer discharge limitations of 300 mg/L, 100 mg/L and 10 mg/L for BOD₅, TKN and TP respectively, it could be seen that the results obtained from Experiment 1-2 meet the discharge requirements. When the after values for COD, TKN and TP are below the dashed limit line, the effluent from the SBR is able to meet the sanitary sewer discharge
requirement. By meeting the sanitary sewer discharge requirement, current surcharges are avoided.

4.3.2 Experiment 1-3

Experiment 1-3 contains a cycle time of 6 hours with 2.5 hours of aeration and 1.5 L of liquid drawn from the system per cycle.

Figure 20 through Figure 22 outlines the initial, final and the allowable sanitary sewer limits for COD, TKN and TP.

Figure 20 – Before, After and Limit of COD Concentration for Experiment 1-3
Experiment 1-3 also demonstrates that the SBR is able to treat the vegetable processing wastewater to be below the sanitary sewer discharge limit and is able to avoid surcharges. From Figure 20 to Figure 22, the after values of COD, TKN and TP are all below the dashed sanitary sewer discharge limit line.
4.3.3 Experiment 1-4

Experiment 1-4 contains a cycle time of 6 hours with 2.5 hours of aeration and 1 L of liquid drawn from the system per cycle.

Figure 23 to Figure 25 outlines the concentration of COD, TKN and TP before and after the use of the SBR. The figures also include a limitation line and outline the sanitary sewer discharge limit mentioned from Table 2.
As it could be seen from these experiments, it may be possible to use the SBR to reclaim vegetable processing wastewater to be below the sanitary sewer discharge limits. The after treatment values from the SBR for COD, TKN and TP are all below the allowable sanitary sewer discharge limit line. It may also be possible to conclude that even with varying operating
parameters, the SBR is still effective in nutrient and organic loading removal for Industrial Partner 1.

### 4.4 Industrial Partner 2

Using the results obtained from Industrial Partner 1, the experiment conditions for Industrial Partner 2 were developed. The conditions were based on the possible removal efficiency achieved found through Industrial Partner 1. One initial change was the dilution of the wastewater obtained from Industrial Partner 2. Due to the difference in vegetable processing the initial concentrations were quite high; COD, TKN and TP values were 16,000 mg/L, 500 mg/L and 50 mg/L respectively. The wastewater required a 10x dilution before being fed into the SBR because the loading would have been too high for the reactor, causing toxic shock. It was found that there was still a statistical difference for COD and TKN between the wastewater collected from Industrial Partner 1 and Industrial Partner 2 after the initial dilution of IP2. The calculations of the statistical difference is included in appendix 7.2.5. The dilution of the wastewater should not be used at full scale, Reduction in organic loading and nutrient concentrations can be achieved with the removal of larger solids particles with the use of filtration or chemical aids.

The difference between Industrial Partner 1 and Industrial Partner 2 are the type of produce that both facilities process. Industrial Partner 2 mainly processes carrots and potatoes, both which require large volumes of water during processing. Industrial Partner 1 on the other hand mainly processes leafy greens and occasionally processes potatoes, carrots, cassavas and other vegetables. When processing leafy greens, the organic loading in the processing wastewater is
not as high as the one for Industrial Partner 2. Thus, the difference in the organic loading and nutrient concentration stems from the types of vegetables that the facility processes daily.

Table 31 outlines the experimental conditions for Industrial Partner 2.

<table>
<thead>
<tr>
<th>Day</th>
<th>Cycle Time (h)</th>
<th>Effluent Withdrawn (L)</th>
<th>Ratio</th>
<th>HRT (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experiment 2-1</td>
<td>271 to 282</td>
<td>8</td>
<td>1.5</td>
<td>0.3</td>
</tr>
<tr>
<td>Experiment 2-2</td>
<td>292 to 296</td>
<td>6</td>
<td>1.5</td>
<td>0.3</td>
</tr>
</tbody>
</table>

Table 32 and 33 outlines the results obtained from the 2 predefined conditions outlined in Table 31.
### Table 32 – Experiment 2-1: 4.5 h of Aeration and 1.5 L of Liquid Drawn

<table>
<thead>
<tr>
<th>Date</th>
<th>Initial</th>
<th>Final</th>
<th>Removal</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>COD</td>
<td>TKN</td>
<td>TP</td>
</tr>
<tr>
<td>14/04/2014</td>
<td>871</td>
<td>51.5</td>
<td>5.6</td>
</tr>
<tr>
<td>15/04/2014</td>
<td>959</td>
<td>54.5</td>
<td>6.0</td>
</tr>
<tr>
<td>16/04/2014</td>
<td>1070</td>
<td>60.5</td>
<td>6.7</td>
</tr>
<tr>
<td>24/04/2014</td>
<td>1020</td>
<td>63.5</td>
<td>6.2</td>
</tr>
<tr>
<td>25/04/2014</td>
<td>1070</td>
<td>61.0</td>
<td>6.5</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Standard Deviation</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Table 33 – Experiment 2-2: 2.5 h of Aeration and 1.5 L of Liquid Drawn

<table>
<thead>
<tr>
<th>Date</th>
<th>Initial</th>
<th>Final</th>
<th>Removal</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>COD</td>
<td>TKN</td>
<td>TP</td>
</tr>
<tr>
<td>05/05/2014</td>
<td>1020</td>
<td>56.0</td>
<td>20.4</td>
</tr>
<tr>
<td>06/05/2014</td>
<td>838</td>
<td>43.1</td>
<td>5.3</td>
</tr>
<tr>
<td>07/05/2014</td>
<td>898</td>
<td>45.8</td>
<td>5.8</td>
</tr>
<tr>
<td>08/05/2014</td>
<td>910</td>
<td>45.3</td>
<td>5.8</td>
</tr>
<tr>
<td>09/05/2014</td>
<td>1280</td>
<td>54.5</td>
<td>7.2</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Standard Deviation</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The high standard deviations obtained in Table 32 and Table 33 would mean that the data obtained for the multiple trials for the same experiment were not close to the mean value. Sparsely collected data would infer that there could have been error whilst collecting the data or that they are not representative of the true value. The standard deviation from Experiment 2-2 for COD removal was the only one that obtained results which were below 10%.

The high deviation obtained from Experiment 2-1 and 2-2 could have been the result from the lack of acclimation time. Due to the difference in wastewater strength, and despite the dilution, the microorganisms needed more time to acclimate to the wastewater. The vegetable processing wastewater from Industrial Partner 2 is not only difficult to treat, but the feeding of different composition wastewater to the same reactor could have caused stress amongst the microorganisms. Moving forward with Industrial Partner 2, more testing on acclimation should be done for the SBR system. In fact, for any biological system being implemented.

Figure 26 to Figure 28 outlines the initial and final concentrations of COD, TKN and TP, which will be discussed in each sub-section separately.
4.4.1 COD

Day 271 to day 282 represents the data obtained from Experiment 2-1. It is apparent that there is little to no COD removal at all. However, from day 292 to day 296, there is a steady increase in COD removal, which again means that the time required for acclimation for Experiment 2-1 may not have been enough.
4.4.2 TKN

From Figure 27, it also appears that for Experiment 2-2, there is a steady decrease in the final effluent concentration of TKN.

4.4.3 TP

Figure 28 will outline the initial and final concentrations of total phosphorous.
From Figure 28, it appears that there is a lack of TP removal for both Experiment 2-1 and 2-2. However, it appears that there is a steady decrease in the final concentration of TP, which is consistent with the data obtained from both the COD and TKN.

With inconsistent data obtained for Experiment 2-1, it could mean that the conditions set were inappropriate for the wastewater that is collected from Industrial Partner 2.

Table 34 outlines some findings with various HRT that are closely related to the ones which are found within the current research.
Table 34 – SBR Removal Efficiency with Various HRT

<table>
<thead>
<tr>
<th>Wastewater</th>
<th>HRT (d)</th>
<th>COD</th>
<th>TKN</th>
<th>TP</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dairy</td>
<td>1</td>
<td>80.2</td>
<td>75.0</td>
<td>N/A</td>
<td>Li and Zhang (2002)</td>
</tr>
<tr>
<td>Potato Starch</td>
<td>1</td>
<td>95.6</td>
<td>N/A</td>
<td>N/A</td>
<td>Wang et al. (2009)</td>
</tr>
<tr>
<td>Malting</td>
<td>1.33</td>
<td>62.5</td>
<td>N/A</td>
<td>N/A</td>
<td>Lo et al. (1998)</td>
</tr>
<tr>
<td>Brewery</td>
<td>1.06</td>
<td>97.3</td>
<td>N/A</td>
<td>N/A</td>
<td>Ling and Lo (1999)</td>
</tr>
<tr>
<td>Domestic</td>
<td>0.66</td>
<td>95.3</td>
<td>97.0</td>
<td>79.7</td>
<td>Chang and Hao (1996)</td>
</tr>
<tr>
<td>Piggery</td>
<td>1</td>
<td>N/A</td>
<td>N/A</td>
<td>97.3</td>
<td>Obaja et al. (2005)</td>
</tr>
</tbody>
</table>

Comparing the obtained literature results in Table 34 with results from Experiment 2-2 it can be concluded that the COD results are similar. The COD, TKN and TP removals were, 71%, 0% and 26% for Experiment 2-2. With similar HRT to that in Table 34, the expected removals from Experiment 2-2 should be about 80%, 80% and 80% for COD, TKN and TP. Since there is a large variation between the expected and actual results with similar HRT, it may mean that there is a higher dependence on removal efficiency with the characteristics of the wastewater rather than the HRT.

Furthermore, for the first experiment, the removal rates for the nutrients and organic loading are not as expected. Even though it is difficult to predict removal efficiencies based simply on the conditions of the SBR, general results from an SBR with moderate temperature and wastewater composition should give COD removal results which are above 50%. Looking back at Table 5 from the data from Lee et al. (2004), the reported COD removal efficiency was 47%. The lack of removal efficiency could have been the result of increase in organic loading for Lee et al. (2004). The research had involved the use of a SBR to remove oily wastewater, but had acclimated to the conditions too quickly for the reactor to handle. However, the COD removal
efficiency was still at 47%, which raises questions on the data found in Table 32 since the COD removal obtained with Experiment 2-1 is almost negligible.

Again, the results found in Table 32 may be explained through the lack in acclimation period. Initially, the SBR was allowed to acclimate with wastewater from Industrial Partner 1 for over 60 days. However, for Industrial Partner 2, the SBR was only allowed to acclimate for 11 days since it was felt that the waste sludge from the Industrial Partner system could be used as seeding sludge. Further, since the nutrient concentration for Industrial Partner 2 is almost double for that of Industrial Partner 1, the conditions of 4.5 h of aeration and 1.5 L of liquid drawn from the system per cycle may not have been suitable. Instead, a longer aeration time and smaller fluid should have been drawn from the system first.

With the results, it is difficult to determine if the optimal results have been found. Even though optimal conditions for Industrial Partner 1 were found, when the same conditions were applied to Industrial Partner 2, it was found that the results lacked consistency, therefore, it is inconclusive to assume that the application of the same condition to multiple sites will produce the same results as well. The condition of having an aeration period of 4.5 hours with 1.5 L of liquid drawn from the system appears to be one of the optimal conditions for Industrial Partner 1 for the highest COD and second highest TKN removal.

Even though the SBR is an extremely versatile and adaptive technology, dilution of the wastewater obtained from Industrial Partner 2 was required to ensure that it did not create a toxic shock to the microbial biomass. From Figure 7, it had been shown that even with steady
acclimation data, the COD had a drastic decrease when the organic loading doubled. Therefore, to minimize the shock between the different wastewater, a 10 fold dilution was required. If the system had been given couple weeks to acclimate in order to adjust to the conditions for Industrial Partner 2, the removal efficiency for COD, TKN and TP would have been greater. The lack of acclimation time and data collection for Industrial Partner 2 was the result of limited time available left for experimentation.

It is not unusual for a system to act differently than the expected, since all systems are slightly different and would require minor adjustments during operation. The lack of nutrient removal efficiency is consistent as Industrial Partner 1, where the carbon to nitrogen and nitrogen to phosphorus ratio is beyond the optimal point. The COD/N for Industrial Partner 2 is also double the recommended value from Komorowska-Kaufman et al. (2006).

Even though the data collected from Industrial Partner 2 does not confirm the results from Industrial Partner 1, it still proves that the SBR can be used for treating vegetable processing wastewater. The slow decline in the effluent of the SBR for the organic loading and nutrients would mean that the reactor only requires a longer reaction period.

**4.4.4 General Results**

Data obtained from a full cycle test for Experiment 2-2 is outlined in Table 35.
Table 35 – Cycle Time for Experiment 2-2 of Industrial Partner 2

<table>
<thead>
<tr>
<th></th>
<th>Influent</th>
<th>Anaerobic</th>
<th>Aerobic</th>
<th>Effluent</th>
</tr>
</thead>
<tbody>
<tr>
<td>COD (mg/L)</td>
<td>1280</td>
<td>504</td>
<td>364</td>
<td>201</td>
</tr>
<tr>
<td>sCOD (mg/L)</td>
<td>1150</td>
<td>171</td>
<td>132</td>
<td>81.3</td>
</tr>
<tr>
<td>TN (mg/L)</td>
<td>55.5</td>
<td>52</td>
<td>47.35</td>
<td>44.2</td>
</tr>
<tr>
<td>Nitrate (mg/L)</td>
<td>0.972</td>
<td>0.786</td>
<td>0.623</td>
<td>0.493</td>
</tr>
<tr>
<td>TKN (mg/L)</td>
<td>54.5</td>
<td>51</td>
<td>46.65</td>
<td>43.65</td>
</tr>
<tr>
<td>TP (mg/L)</td>
<td>7.2</td>
<td>5.32</td>
<td>5.41</td>
<td>3.79</td>
</tr>
<tr>
<td>VA (mg/L)</td>
<td>238</td>
<td>54.6</td>
<td>41.6</td>
<td>25</td>
</tr>
<tr>
<td>Nitrite (mg/L)</td>
<td>0.043</td>
<td>0.074</td>
<td>0.067</td>
<td>0.047</td>
</tr>
</tbody>
</table>

Samples of the anaerobic and aerobic stages from Experiment 2-2 were collected after 30 minutes of the initial starting phase period. The total nitrogen within the water sample is decreasing, which is expected since nitrification-denitrification process allows for the formation of nitrogen gas to be released. From Table 35, there is an increase of nitrite during the anaerobic phase. The increase in concentration could have been the result of the conversion from ammonium to nitrite during the nitrification process which was then quickly converted to nitrate. Furthermore, there should have been a release of phosphorus during the anaerobic stage (Loosdrecht et al., 1997) and an excess uptake during the aerobic stage, which was not demonstrated during this sample run.

The average removal efficiency for TKN for Experiment 2-1 is 15.8%. The removal efficiency for COD and TP for Experiment 2-2 is 71.2% and 25.6% respectively.

Figure 29 and 30 outlines the comparisons for the results obtained between the 2 experimental conditions for COD, TKN and TP.
When comparing the results obtained from IP1 and IP2, it can be observed that there is a large difference between the removal efficiencies with its respected nutrient parameter in question.

Figure 29 – Experiment 1-2 and 2-1 Results for IP1 and IP2

Figure 30 – Experiment 1-3 and 2-2 Results for IP1 and IP2
These large nutrient removal differences could have been the result of many factors, but one major factor could have been the composition of the wastewater itself. Observing the initial nutrient concentrations, it was found that with similar organic loading values the initial values for TKN is nearly doubled for Industrial Partner 2. With reduced time in the acclimation for Industrial Partner 2, there could have been a toxic shock amongst the microorganism culture which could have resulted in the lack of removal.

The results from Industrial Partner 2 may not have been as conclusive as Industrial Partner 1 due to the allotted timeframe. If more time was allotted, the same series of experiments could have been conducted for Industrial Partner 2. Ideally, the acclimation period should have been over 1 month or until the removal efficiency only fluctuated between 10% of the mean value. Further, the equipment used for the SBR was needed for a membrane filtration set up within the same research group. The focus of the membrane filtration was for Industrial Partner 2 wastewater.

Even though the wastewater for Industrial Partner 2 was not as extensively studied as Industrial Partner 1, the optimization process would be identical. After setting an initial condition with a length acclimation period, the appropriate parameters could be altered and the effects of them could be observed. Since the organic loading and nutrient concentration for Industrial Partner 2 is much greater than that of Industrial Partner 1, the HRT for Industrial Partner 2 should be longer. Further, the focus should be on the volume of liquid drawn from the system, rather than the aeration period, from the results found from Industrial Partner 1.
Although there are vast differences between the results obtained from Industrial Partner 1 and 2, it can still be concluded that the use of a SBR can treat vegetable processing wastewater. The results obtained from Industrial Partner 1 was able to meet the sanitary sewer discharge limits, thereby eliminating or reducing future surcharges. The same conditions that were used in Industrial Partner 1 were applied to Industrial Partner 2 in hopes of achieving the same results. Even though it did not give equivalent results, the trend of effluent values obtained proved that removal efficiency was rising during Experiment 2-2, which meant that the SBR can adapt to changes in the composition of the wastewater quickly. All systems built for wastewater treatment systems would still require minor adjustments when upsizing from the lab scale to the pilot or full scale.

4.5 UV Disinfection for B. subtilis

Reuse of the treated wastewater is an important goal, as opposed to using fresh water for cleaning and processing. The reduction in fresh water usage could reduce the cost of incoming water and outgoing effluent wastewater. However, in the food sector it is important to reduce microbial population to ensure safe water if the water is to be reused onsite. One of the disinfectants used in the food sector is UV.

The three most common types of technology used for disinfection are ultraviolet, advanced oxidation processes and chlorination. Chlorination is extremely effective in destroying microorganisms and it would also leave a residual within the treated water. However, the use of chlorination would create unwanted by-products such as TTHM. The effectiveness of advanced oxidation processes is similar to that of chlorination. Further, ozone is produced on site as opposed to being purchased and shipped, which could reduce costs. However, ozone is
extremely reactive and does not leave a residual within the water. UV disinfection is easier to control and extremely effective against viruses. UV disinfection was used for this research due to its versatility in arrangement, effectiveness and operation.

Chevrefils et al. (2006) compiled a list of minimum UV dosages required for the log reductions of various bacteria, spores and viruses. Chang et al. (1985) had determined that the minimum dosage rate for 1 log removal of B. subtilis was found to be 40 mJ/cm$^2$. B. subtilis was used as the surrogate since it is the most resilient to UV disinfection. Thus, if using UV disinfection log 5 removal could be achieved, then it should also be able to achieve log 5 removal for other various microorganisms, such as E. coli as well. Using Equations 9 to 14, with a central irradiance of 0.420 mW/cm$^2$ and an absorbance value of 0.368, Table 35 was developed to determine the time needed to deliver the required dosage. The absorbance value of 0.368 corresponds to Experiment 1-6 for Industrial Partner 1. This value was chosen to represent the capability of microbial reduction with the use of UV disinfection. The higher the absorbance value, the lower the applied germicidal irradiance. Therefore, if it was possible to obtain log 5 removal result with the lowest applied germicidal irradiance, then it should also be able to apply for the remaining wastewater samples as well. The remaining absorbance values for the remaining experiments could be found in Appendix 7.1.

The difference in absorbance values for the varying samples of water could be the result of the microbial biomass becoming more filamentous and thus obtaining more suspended solids. Further, since influent water samples were collected weekly, the influent samples could have also had more suspended solids in the effluent as well.
Therefore, if our goal is to achieve a log 5 removal of B. subtilis from the treated wastewater, then there would be a need for 13.7 minutes of disinfection based on Table 36.

The limitations of UV disinfection include uncertainty with the delivery dosage. Kuo et al. (2003) discussed the many different scenarios of the deviance of the delivery dose. Other than the 4 factors (water, divergence, reflection and petri) which affect the dosage that is directly applied onto the sample, it could also be possible that the size of the petri dish and type of petri dish used could also cause reflectance.

Table 37 outlines the initial concentration of B. subtilis as it enters into the collimated beam apparatus after dilution. The MPN is 2.65E+07 for the initial concentration of B. subtilis.

<table>
<thead>
<tr>
<th>Log Removal</th>
<th>UV Fluence (mJ/cm²)</th>
<th>Time (mins)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>40</td>
<td>2.7</td>
</tr>
<tr>
<td>2</td>
<td>80</td>
<td>5.5</td>
</tr>
<tr>
<td>3</td>
<td>120</td>
<td>8.2</td>
</tr>
<tr>
<td>4</td>
<td>160</td>
<td>10.9</td>
</tr>
<tr>
<td>5</td>
<td>200</td>
<td>13.7</td>
</tr>
<tr>
<td>6</td>
<td>240</td>
<td>16.4</td>
</tr>
<tr>
<td>7</td>
<td>280</td>
<td>19.1</td>
</tr>
<tr>
<td>8</td>
<td>320</td>
<td>21.9</td>
</tr>
</tbody>
</table>

Table 37 – Original Concentration of B. subtilis

<table>
<thead>
<tr>
<th>Dilution</th>
<th># of Colonies</th>
<th>cfu/mL</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>TNTC</td>
<td>N/A</td>
</tr>
<tr>
<td>4</td>
<td>36</td>
<td>3.60E+06</td>
</tr>
<tr>
<td>5</td>
<td>16</td>
<td>1.60E+07</td>
</tr>
<tr>
<td>6</td>
<td>6</td>
<td>6.00E+07</td>
</tr>
</tbody>
</table>
By knowing the UV fluence of the lamp and applying correction factors, the appropriate contact time of 13.7 minutes was found for a log 5 removal from Table 36. The numbers of colonies that were on the plate was counted and corrected for the appropriate concentration as noted in Table 38.

<table>
<thead>
<tr>
<th>Dilution</th>
<th># of Colonies</th>
<th>cfu/mL</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>4</td>
<td>4.00E+01</td>
</tr>
<tr>
<td>1</td>
<td>12</td>
<td>1.20E+03</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>4.00E+03</td>
</tr>
<tr>
<td>3</td>
<td>5</td>
<td>5.00E+04</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>0.00E+00</td>
</tr>
</tbody>
</table>

The most probable number for the log 5 reduction concentration of B. subtilis should be 1.10E+04. Comparing the initial concentration of B. subtilis at 2.65E+07 with the final value of 1.10E+04 only a difference of 3 log is found. Reasons for the deviation include that the actual germicidal irradiation that is applied could have been smaller than the required germicidal irradiation through the four main correction factors of water, petri, reflection and divergence. The germicidal irradiation could have been smaller if the sensitivity was higher, if the UV fluence from the lamp was initially smaller or if the recorded absorbance was higher. Since the UV fluence is based off a $D_{10}$ value, the applied dosage could have actually been less than the required. Further, since B. subtilis is a spore and one of the more difficult microorganisms to inactivate, the log removal may not be linear and thus, to remove at a higher log removal would have required an exponential UV dosage.
The goal of the UV disinfection is to reduce the B. subtilis culture by 5 logs from standards. Since the current data only provides 3 logs, it is currently not possible to deduce the possibility of using UV disinfection for microbial disinfection at this stage.

In conclusion, UV disinfection with treated wastewater from the SBR does not seem feasible. The turbidity of the water reduces the germicidal irradiation greatly and thus requires a long contact time. The typical contact time for UV disinfection would be between 20 to 30 (USEPA, 1999b) seconds. With required contact times that are longer than 10 minutes for the treatment of wastewater from the SBR, it is difficult to rationalize the addition of UV disinfection at this stage. However, if a filtration system, such as membranes were used to reduce the turbidity, then it may be possible to apply UV disinfection into the system.

4.6 Application of Findings

The following section will outline the uses of this research and the possible cost that it would take to build the system.

4.6.1 Application

Using the data obtained from this research, it would be possible to know if the SBR is capable of removing organic loading and nutrients from the wastewater that could meet the sanitary sewer discharge limits. So far, the data suggests that it is possible to remove the organic loading and nutrients from one of the industrial partners. Further, there is confidence that the SBR can remove the organic loading and nutrients from the second industrial partner as well with the appropriate acclimation period.
4.6.2 Estimated Cost Analysis

The cost analysis for the system was based on data obtained from Industrial Partner 2, located in the City of Toronto, as surcharges for Industrial Partner 1 were unavailable. Table 39 contains the provided data from Industrial Partner 2 in year 2010. Even though the SBR process has not yet been optimized for Industrial Partner 2 yet, literature proves that it could be possible to reduce organic loading and nutrient concentrations to below acceptable surcharge levels. Bartone et al. (1992) had initial COD values of 10,000 mg/L and was still able to achieve 93% removal. Thus, with the correct acclimation period, it would be possible to treat the wastewater from Industrial Partner 2 directly. The following cost estimate is based purely on the wastewater flow to the sanitary sewer. Thus, the exact same principles can be applied for Industrial Partner 1 if the flow and incurred surcharges were made available.

Further, cost analysis for Industrial Partner 2 was preferred over Industrial Partner 1 for its strength in wastewater. The organic loading and nutrient concentration for Industrial Partner 2 was also much greater than that of Industrial Partner 1. Thus, if surcharges were to have incurred, given the same flow rate, then the mass amount surcharged would have been greater for Industrial Partner 2.

Table 39 – Flow Rate of Industrial Partner 2 in 2010

<table>
<thead>
<tr>
<th>Quarter</th>
<th>Flow (m³/y)</th>
<th>Surcharge ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>35,565</td>
<td>16,359.59</td>
</tr>
<tr>
<td>2</td>
<td>37,439</td>
<td>15,925.14</td>
</tr>
<tr>
<td>3</td>
<td>36,518</td>
<td>13,103.32</td>
</tr>
<tr>
<td>4</td>
<td>36,274</td>
<td>11,434.02</td>
</tr>
</tbody>
</table>
The average flow rate is 36,449 m$^3$/y and the total surcharge is $56,822 in 2010 which is $61,344 with the inflation to 2014. With a safety factor of 1.5 the flow rate is 54,673.5 m$^3$/y or 0.04 MGD.

Based on a fact sheet developed by the United States Environmental Protection Agency (USEPA, 1999c), the equipment cost in 1998 would be $142,038, which in present day would cost $194,703 with additional operation and maintenance being $40,000 a year. The payback period is dependent on the difference between the surcharge rate which would have been charged per year in addition to the operation and maintenance per year. Assuming that there is a consistent inflation rate of 2% every year on the operation and maintenance cost, the amount of payback will be reduced yearly.

Table 40 shows the payback period required for the SBR system that is to be built.

<table>
<thead>
<tr>
<th>Year</th>
<th>O&amp;M ($)</th>
<th>Payback ($)</th>
<th>Remaining ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>40,000</td>
<td>21,344.24</td>
<td>173,358.76</td>
</tr>
<tr>
<td>2</td>
<td>40,800.00</td>
<td>20,544.24</td>
<td>152,814.52</td>
</tr>
<tr>
<td>3</td>
<td>41,616.00</td>
<td>19,728.24</td>
<td>133,086.28</td>
</tr>
<tr>
<td>4</td>
<td>42,448.32</td>
<td>18,895.92</td>
<td>114,190.36</td>
</tr>
<tr>
<td>5</td>
<td>43,297.29</td>
<td>18,046.95</td>
<td>96,143.41</td>
</tr>
<tr>
<td>6</td>
<td>44,163.23</td>
<td>17,181.01</td>
<td>78,962.40</td>
</tr>
<tr>
<td>7</td>
<td>45,046.50</td>
<td>16,297.74</td>
<td>62,664.66</td>
</tr>
<tr>
<td>8</td>
<td>45,947.43</td>
<td>15,396.81</td>
<td>47,267.84</td>
</tr>
<tr>
<td>9</td>
<td>46,866.38</td>
<td>14,477.86</td>
<td>32,789.98</td>
</tr>
<tr>
<td>10</td>
<td>47,803.70</td>
<td>13,540.54</td>
<td>19,249.44</td>
</tr>
<tr>
<td>11</td>
<td>48,759.78</td>
<td>12,584.46</td>
<td>6,664.98</td>
</tr>
</tbody>
</table>

Even though the time period to fully pay off the SBR would be approximately 12 years, there is a potential for a shorter payback period. In 2014, not all municipalities enforce surcharge for TKN and TP. The surcharges outlined for Industrial Partner 2 in 2010 are only charged for the greater
two of, suspended solids and biological oxygen demand. If municipalities intend on increasing the surcharges or if more parameters are charged, then the potential for the payback period could be reduced. However, since the data obtained is a just a cost estimate, it is difficult to determine the true cost of the system without further inquiries from manufacturers. Thus, the payback period of 12 years should only be used as a guideline.

The 12 year payback period is a reasonable amount of time, especially when considering that it is designed with a safety factor of 1.5 for the flow rate. With municipalities requiring smaller onsite treatment systems to be built, having a system which would only require the amount that is typically used for surcharges to pay for both the operation and capital cost of the system is ideal. Also, the operation of the system may only require minimal amount of qualified personnel to operate it to ensure that ideal removal efficiencies of organic loading and nutrients are achieved.

The implementation of a SBR would require the hydraulic retention time to size the reactor. The smaller the HRT, the more wastewater the SBR could treat daily. The SRT and MLSS concentration is used to determine the healthiness and growth of the microorganisms within the reactor. Without biomass in the reactor, no to little removal efficiency will be achieved during the reaction period.

The challenge with biological systems is that many parameters are able to affect the performance of the reactor. If the temperature of the reactor is decreased, the removal efficiency of the organic loading and nutrient removal would also decrease. Also, it is difficult to control the rate
of growth of the biomass and the strains of microorganisms that grow. For identical operations, one reactor may have better settleability than another if one reactor has more filamentous growth.

Further, all biological systems are unique. Even if a full scale model had been built for Industrial Partner 1, it would have still required minor modifications to achieve organic loading and nutrient removal efficiencies to be below the sanitary sewer discharge limits. Therefore, it is not surprising that the same challenges that existed for Industrial Partner 1 also applies to Industrial Partner 2, or in the laboratory. The challenge with the dilution of the wastewater from Industrial Partner 2 may include a holding tank. A tank might be installed to dilute the influent wastewater with a portion of that of the effluent.

Personal opinion would suggest that the installation of a system to reduce the nutrient and organic loading rates should be installed. The operation of the SBR is not a difficult one, so operators would not need extensive training.

The monetary means of the operation and installation of a technology to remove nutrients is of importance, but it is also important to consider other potential benefits as well. There could be a potential for government subsidy in the future. It may also be possible to convert the SBR to generate electricity for use within the facility as a microbial fuel cell (Nevin and Lovley, 2010). The claim that the facility is operating at near off grid conditions could also encourage consumer confidence that the company is a leader in its field and establish a stronger connection.
Furthermore, municipalities are now requiring decentralized systems to be installed onsite of the various vegetable processing facilities to treat the wastewater generated as the central facilities cannot handle the flow and organic loading. From a taxpayer perspective, they also do not want to expand the central facilities.

Furthermore, research has also been conducted to find the importance of green initiatives on purchasing consumers. Lea and Worsley (2008) had conducted a survey to determine which factors affect the everyday consumer the most. Within the survey, it was determined that 35% of consumers strongly wanted farmers to care more about the environment. Consumers had interpreted that the care of the environment had included factors such as reduction in water usage. The implementation of the SBR could equate to a decrease in fresh water used within the system, if recycled water is used onsite. Therefore, promoting this benefit could increase the self-image of the facility. However, care must also be taken when promoting green claims since they are often critiqued by pessimism (Boye and Arcand, 2013).
Chapter 5: Conclusion and Recommendation

The goal of the research is to reduce the effluent vegetable processing wastewater to be below the allowable sanitary sewer discharge limits to avoid surcharges. Since there are no set provincial regulations, municipalities determine the rate and concentration for allowable discharge for each parameter. For this research a sequencing batch reactor was selected to reduce the parameters of interest (chemical oxygen demand, total Kjeldahl nitrogen and total phosphorus).

Based on the experiments completed, the following conclusions that have been made:

- SBR is capable of treating vegetable processing wastewater to sanitary sewer discharge limits
  - Optimal conditions for Industrial Partner 1 was 2.5 hours of aeration with 1.0 L of water decanted from the system per cycle, having an SRT of 25 d and a MLSS of 12,500 mg/L
  - Optimal conditions for Industrial Partner 2 was not found as the waste strength was considerably higher than Industrial Partner 1. It is believed that the biomass needed more time to acclimatize to the waste.

- Further treatment was still required to reduce nutrient levels to be below storm sewer discharge limits

- The effect of liquid exchange is greater for an SBR than that of aeration

- Longer HRT was required for TP removal

- UV disinfection does not currently work. The major cause would be the high turbidity in the effluent samples from the SBR.
Recommendations for this research are as follows:

- Allowing a longer acclimation period for Industrial Partner 2 before doing testing
- Allowing for a longer testing period for both Industrial Partner 1 and 2
- Allowing for more frequent testing for all experiments for more data points
- Allowing for testing of ions and VFA to determine the cause of the lack of phosphorus removal
- Allowing for the use of a membrane after the SBR to determine the reduction of absorbance prior to UV
- Optimal conditions for Industrial Partner 2 needs to be determined with further experimentation
Chapter 6: References


Hach, 2014. (Personal communication 20.08.2014).


Chapter 7: Appendix

7.1 Raw Data

Table 41 – Raw Data for COD, TKN and TP

<table>
<thead>
<tr>
<th>Day</th>
<th>Date</th>
<th>COD Initial</th>
<th>COD Final</th>
<th>TKN Initial</th>
<th>TKN Final</th>
<th>TP Initial</th>
<th>TP Final</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>18/07/2013</td>
<td>1850</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>19/07/2013</td>
<td>1680</td>
<td>59.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
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### Table 42 – Absorbance Values for Various Experiments from Industrial Partner 1

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### Table 43 – Mixed Liquor Suspended Solids Data During Acclimation

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7.2 Sample Calculations

7.2.1 Biological Oxygen Demand Range

To determine the range of dilutions required to calculate the biological oxygen demand, the following equations were used. The BOD$_5$ estimate, is an estimated guess of what the concentration of the BOD$_5$ may be. Since the COD concentration is generally at 1500 mg/L, it is assumed that the BOD$_5$ could be at 1000 mg/L. According to standard method, the minimum depletion of a sample is 2 mg/L to be considered valid. Assuming at maximum oxygen saturation to be at 9 mg/L and at the remaining depletion a dissolved oxygen concentration of 1 mg/L, then the maximum depletion is 8 mg/L.

\[
\text{Minimum Volume} = \frac{\text{Minimum Depletion} \times \text{Bottle Volume}}{\text{BOD Estimate}}
\]

\[
\text{Maximum Volume} = \frac{\text{Maximum Depletion} \times \text{Bottle Volume}}{\text{BOD Estimate}}
\]

Bottle volume = 300 mL
BOD$_5$ estimate = 1000 mg/L
Minimum depletion = 2 mg/L
Maximum depletion = 8 mg/L

\[
\text{Minimum Volume} = \frac{2 \text{ mg} \cdot 300 \text{ mL}}{1000 \text{ mg} \cdot \text{L}} = 0.6 \text{ mL}
\]

\[
\text{Maximum Volume} = \frac{8 \text{ mg} \cdot 300 \text{ mL}}{1000 \text{ mg} \cdot \text{L}} = 2.4 \text{ mL}
\]

Therefore, the range required for the BOD$_5$ dilutions will be set at 0.5 mL, 1 mL, 1.5 mL, 2 mL and 2.5 mL.
### 7.2.2 BOD$_5$ Data

Conducted: March 21, 2014

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#### Seeded Controls

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#### Samples

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<td>602.4</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>580.3</strong></td>
<td></td>
</tr>
</tbody>
</table>
7.2.3 Payback Period

According to Table 39, the average flow rate of 2010 is 36449 m$^3$/y. Applying a safety factor of 1.5, the following flow rate could be found.

\[
\text{Flow Rate} = 36449 \frac{m^3}{\text{year}} \times SF = 54673.5 \frac{m^3}{\text{year}} \times \frac{1000 \text{ L}}{m^3} \times \frac{\text{year}}{365 \text{ day}} \times \frac{0.264172 \text{ gal}}{\text{L}}
\]

\[
= 39,570 \frac{\text{gal}}{\text{day}}
\]

Flow rate = 0.03957 MGD

Using the information provided on USEPA (1999c), interpolation of the equipment cost could be found.

\[
\text{Equipment Cost} = \frac{\text{Flow Rate} - \text{Lower Flow}}{\text{Higher Flow} - \text{Lower Flow}} \times (\text{Higher Cost} - \text{Lower Cost}) + \text{Lower Cost}
\]

\[
= \frac{0.03957 \text{ MGD} - 0.015 \text{ MGD}}{1 \text{ MGD} - 0.015 \text{ MGD}} \times ($339000 - $137000) + $137000
\]

\[
= $142,038 \text{ in 1998}
\]

According to inflation to 2014, the cost would be $194,703.

According to USEPA (1999c), the maintenance and operation of the SBR is between $800 to $2,000 per million gallons of water treated.

\[
\text{O&M Cost} = \text{Flow} \times \text{Rate} = 14.44 \frac{\text{million gallon}}{\text{year}} \times 2000 = $28,886
\]

Converting the O&M cost from 1998 to 2014, the cost would be $40,000.
The surcharge cost for the year 2010 is $56,822.07 and when converted to 2014 the cost is $61,344.24. The inflation rate used is 2%.

<table>
<thead>
<tr>
<th>Type of Cost</th>
<th>Cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equipment Cost</td>
<td>194,703</td>
</tr>
<tr>
<td>Surcharge</td>
<td>61,344.2</td>
</tr>
<tr>
<td>O&amp;M</td>
<td>40,000</td>
</tr>
</tbody>
</table>

Payback \((Year \ n)\) = Equipment Cost – (Surcharge – O&M * Interest\(^n\))

Payback \((Year \ 1)\) = 194703 – (61344.24 – 40000 * 1.02\(^0\)) = $173359

Payback \((Year \ 2)\) = 173359 – (61344.24 – 40000 * 1.02\(^1\)) = $152815

Payback \((Year \ 3)\) = 152815 – (61344.24 – 40000 * 1.02\(^2\)) = $133086

Continuing this calculation, it was found that the final year of payback would be 12.

**7.2.4 UV Disinfection**

To determine the time required for a predefined dose, the UV fluence must be found.

\[ Log \ Removal = \frac{UV\ Fluence}{UV\ Sensitivity} \]

Log removal = 5
UV sensitivity = 40 mJ/cm\(^2\)

\[ UV\ Fluence = Log\ Removal \times UV\ Sensitivity = 5 \times 40 = 200\ mJ/cm^2 \]

With the UV fluence, the time required could then be found with the correct germicidal irradiance.

\[ Germicidal\ Irradiance \times 60 \times time\ (minutes) = UV\ Fluence \]
The central irradiance is found to be 0.420 mW/cm$^2$, and needs to be corrected as the germicidal irradiance.

\[
\text{time (minutes)} = \frac{\text{UV Fluence}}{\text{Germicidal Irradiance} \times 60}
\]

The time in minutes is determined by the germicidal irradiance and its relation to the central irradiance.

\[\text{Germicidal Irradiance} = \text{Central Irradiance} \times \text{Reflection} \times \text{Petri} \times \text{Water} \times \text{Divergence}\]

The reflection factor for an air-water medium is found to be 0.025 (Meyer-Arendt, 1984).

\[\text{Reflection Factor} = 1 - 0.025 = 0.975\]

\[\text{Petri Factor} = 1\]

The absorbance for Experiment 1-6 is 0.368/cm according to Table 42 and the depth of the solution is 1.2 cm.

\[\text{Water Factor} = \frac{1 - 10^{-al}}{al \ln(10)} = \frac{1 - 10^{-0.368 \times 1.2}}{0.368 \times 1.2 \ln(10)} = 0.628\]

The length from the lamp to the sample is 22.5 cm.

\[\text{Divergence Factor} = \frac{L}{L + l} = \frac{22.5}{22.5 + 1.2} = 0.949\]

\[\text{Germicidal Irradiance} = 0.420 \frac{\text{mW}}{\text{cm}^2} \times 0.975 \times 1 \times 0.628 \times 0.949 = 0.244 \frac{\text{mW}}{\text{cm}^2}\]

\[\text{time (minutes)} = \frac{200 \frac{\text{mj}}{\text{cm}^2}}{0.244 \frac{\text{mW}}{\text{cm}^2} \times 60} = 13.7 \text{ min}\]

7.2.5 Statistical Analysis of IP1 and IP2 (McBean and Rovers, 1998)

To determine if the data obtained from Industrial Partner 1 and 2 is significantly different a statistical test must be used. The t-test will be used as the statistical test. However, before it is possible to perform the t-test, the assumptions for the t-test must first be found. The 3
assumptions for the t-test are having the population normally distributed, equal variance and independent. The data obtained for both industrial partners are at 2 separate locations, with different technologies currently installed and thus able to fulfill independency. To determine if the data is normally distributed, a coefficient of variance was found for both data sets for COD. Further, the null hypothesis of the t-test is that there is no significant between the data.

<table>
<thead>
<tr>
<th>Table 45 – IP1 and IP2 Data for COD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Industrial Partner</td>
</tr>
<tr>
<td>---------------------</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
</tbody>
</table>

Both of the data sets contain a coefficient of variance less than 1, representing both of the data sets normally distributed.

The pass of the F-test would equate to equal variances.

\[
F = \frac{\text{greater estimate of the variance of the population}}{\text{lesser estimate of the variance of the population}}
\]

\[
F = \frac{s_1^2}{s_2^2} = \frac{522.69^2}{129.81^2} = 16.43
\]

Using an F-test table with the greater degree of freedom as 69 and the lesser degree of freedom as 9, the \(F_{\text{critical}}\) value was found to be 2.88. Therefore, since the F value was found was greater than the \(F_{\text{critical}}\), the two data sets have unequal variances. Since the data sets do not have equal variances, a modification of the t-test must be used instead. The Cochran’s test was used accordingly to formulate the \(t^*\) and \(t_c\).

\[
t^* = \frac{|x_1 - x_2|}{\sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}} = \frac{|1826.43 - 933.6|}{\sqrt{\frac{522.69^2}{70} + \frac{129.81^2}{10}}} = 11.94
\]
The $t_1$ and $t_2$ is determined as $1.645$ and $1.833$.

Since $t^* > t_c$, there is a significant difference between the data for COD and the null hypothesis is rejected.

The same procedure is carried out for both TP and TKN.

Since the F value is smaller than the $F_{critical}$, the data sets have equal variance and the t-test can be utilized.

The summarized data for TP of IP1 and IP2 is then included within Table 46.

<table>
<thead>
<tr>
<th>Industrial Partner</th>
<th>Mean</th>
<th>Standard Deviation</th>
<th>Coefficient of Variance</th>
<th>Sample Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9.48</td>
<td>5.52</td>
<td>0.582</td>
<td>37</td>
</tr>
<tr>
<td>2</td>
<td>7.53</td>
<td>4.55</td>
<td>0.604</td>
<td>10</td>
</tr>
</tbody>
</table>

Since the F value is smaller than the $F_{critical}$, the data sets have equal variance and the t-test can be utilized without manipulation. The pooled variance was then found with the following equation.

$$F = \frac{s_1^2}{s_2^2} = \frac{5.52^2}{4.55^2} = 1.47$$

The standard error of difference must then be found.

$$S_m = \sqrt{\hat{s}^2 \left( \frac{1}{n_1} + \frac{1}{n_2} \right)} = \sqrt{28.5 \left( \frac{1}{37} + \frac{1}{10} \right)} = 1.90$$

Finally, the value of the t-test was then found and compared to the $t_c$ obtained from student t-tables.
With the degree of freedom of 45 and a 95% confidence interval with a one tailed test, the $t_c$ is found to be 1.679. Since $t^*$ is smaller than $t_c$, the null hypothesis is not rejected and there is no significant difference between the 2 sets of data.

The same analysis was then proceeded for TKN and summarized in Table 47.

<table>
<thead>
<tr>
<th>Industrial Partner</th>
<th>Mean</th>
<th>Standard Deviation</th>
<th>Coefficient of Variance</th>
<th>Sample Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>16.72</td>
<td>8.49</td>
<td>0.507</td>
<td>42</td>
</tr>
<tr>
<td>2</td>
<td>53.56</td>
<td>7.1</td>
<td>0.132</td>
<td>10</td>
</tr>
</tbody>
</table>

$$F = \frac{s_1^2}{s_2^2} = \frac{8.49^2}{7.1^2} = 1.43$$

$$\hat{s}^2 = \frac{(42 - 1)8.49^2 + (10 - 1)7.1^2}{42 + 10 - 2} = 68.2$$

$$S_m = \sqrt{68.2 \left( \frac{1}{42} + \frac{1}{10} \right)} = 2.9$$

$$t^* = \frac{|16.72 - 53.56|}{\sqrt{\left( \frac{42 + 10}{42 \times 10} \right) \left( \frac{42 - 1)8.49^2 + (10 - 1)7.1^2}{42 + 10 - 2} \right)}} = 12.7$$

With a degree of freedom of 50 and a 95% confidence interval, the $t_c$ of a one tailed test is found to be 1.676. Since the $t^*$ is greater than $t_c$, the null hypothesis is rejected and there is significant difference between the two sets of data.
7.2.6 SRT and MLSS

The calculation of the SRT is measured as the total volume of the system divided by the amount of sludge that is wasted daily.

\[ SRT = \frac{Total\ Volume}{Sludge\ Wasted} = \frac{5L}{0.2 \frac{L}{day}} = 25 \text{ days} \]

The MLSS is calculated as the difference in the dry weight of a sample. The following is a sample calculation taken from July 4, 2013.

\[ MLSS = \frac{Before - After}{Sample\ Volume} = \frac{4.3555\ g - 4.3806\ g}{2\ mL} = 12.55\ \frac{g}{L} \]