

**COMBINED BIOLOGICAL AND ADVANCED OXIDATION PROCESSES FOR THE
TREATMENT OF AN ACTUAL SLAUGHTERHOUSE WASTEWATER**

by

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ABSTRACT

Combined Biological and Advanced Oxidation Processes for the Treatment of an Actual Slaughterhouse Wastewater

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Environmental protection initiatives and increasing market demand for green practices are driving the meat processing industry to consider sustainable methods for wastewater treatment of slaughterhouse wastewater. On-site treatment is the preferred option to treat the slaughterhouse effluents for water reuse and potential energy recovery due to the conversion of organics into biogas. A thorough review of advancements in slaughterhouse wastewater characteristics, treatment, and management in the meat processing industry, environmental impacts, health effects, and regulatory frameworks relevant to the slaughterhouse wastewater management is presented in this study. Significant progress in high-rate anaerobic treatment, nutrient removal, advanced oxidation processes, and combined processes for an actual slaughterhouse wastewater treatment are highlighted. The optimization of individual and combined processes was performed in this study using quadratic modeling, degradation mechanisms, and response surface methodology to maximize CH₄ yield and the removal of TOC and TN while minimizing TSS and H₂O₂ residuals. The effects of the flow rate, pH, influent TOC concentration, H₂O₂ dosage, and their interaction on the overall treatment efficiency and CH₄ yield were studied. In the final part of this study, an optimized combined anaerobic–aerobic and UV/H₂O₂ system with recycle was evaluated using a cost-effectiveness analysis by minimizing treatment time, electrical energy consumption, and the overall incurred treatment costs. The agreement between model predictions and experimental values indicated that the proposed models could describe the performance of individual and combined systems for actual SWW treatment. The maximum TOC and TN removals of 91.29 and 86.05%, CH₄ yield of 55.72%, and minimum H₂O₂ residual of 1.45% were found at optimum conditions of influent TOC concentration of 626 mg/L, feed flow rate of 45 mL/min, H₂O₂ dosage of 350 mg/L, and pH of 6.59. The minimum total retention time was determined to be 10 h with individual residence times of 6.82 h, 2.40 h, and 47 min in the ABR, AS bioreactor, and UV/H₂O₂ photoreactor, respectively. A minimum electrical power consumption of 0.0194 kWh for an overall treatment cost of 0.12 \$/m³ were obtained based on the cost-effectiveness analysis. Results show that the application of combined biological and advanced oxidation processes is useful for on-site slaughterhouse wastewater treatment.

Keywords: Slaughterhouse wastewater, anaerobic digestion, activated sludge, advanced oxidation processes, process optimization, cost-effectiveness analysis.

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*This doctoral dissertation is dedicated to the love of my life
Liseth Sierra Vitola
whose unconditional love, patience, and sacrifice
has encouraged me to improve every day*

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CHAPTER 1

INTRODUCTION

Water and wastewater treatment has become crucial for the continuing development of current society. The progressively stricter standards for effluent discharge worldwide have made the development of advanced wastewater treatment technologies necessary (Environment Canada, 2000; US EPA, 2004; World Bank Group, 2007). Moreover, the decreasing availability of freshwater resources along with the growing population has rearranged the objectives in the wastewater treatment field from disposal to reuse and recycling. As a result, a high level of treatment efficiency has to be achieved. Given the differences in location, economic resources, and living standards of different countries and characteristics of water and its pollutants, many nations have adopted diverse techniques for water and wastewater treatment (Daigger, 2009).

The meat-processing sector produces large amounts of slaughterhouse wastewater (SWW) due to the slaughtering of animals and birds and cleaning of the slaughterhouse facilities and meat processing plants (MPPs). The meat processing industry uses 24% of the total freshwater consumed by the food and beverage industry and up to 29% of that consumed by the agricultural sector worldwide (Mekonnen and Hoekstra, 2012; Gerbens-Leenes et al., 2013). Moreover, the global production of beef, pork, and poultry meat has been doubled in the past decade and is projected to grow steadily until 2050. Furthermore, the number of slaughterhouse facilities are increasing, which results in an expected higher volume of slaughterhouse wastewater (SWW) to be treated.

Slaughterhouses are part of a large industry, which is common to numerous countries worldwide where meat is an important part of their diet. Therefore, SWWs require significant treatment for a safe and sustainable release to the environment (Johns, 1995). Therefore, the treatment and disposal of wastewater from slaughterhouses and MPPs are an economic and public health necessity (Debik and Coskun, 2009). SWWs have been considered as an industrial waste in the category of agricultural and food industries and classified as one of the most harmful wastewaters to the environment by the United States Environmental Protection Agency (US EPA) since SWW discharge may cause deoxygenation of rivers and contamination of groundwater (US EPA, 2004).

Slaughterhouse wastewater (SWW) effluents are becoming one of the major agribusiness concerns because of the elevated amounts of water used during slaughtering, processing, and cleaning of the abattoir facilities. Although physical, chemical, and biological treatment can be used for SWW degradation, each treatment process has different benefits and drawbacks depending on the SWW characteristics, best available technology, jurisdiction, and regulations (Tabrizi and Mehrvar, 2004; Barrera et al., 2012; Franke-Whittle and Insam, 2013; Bustillo-Lecompte and Mehrvar, 2015; Valta et al., 2015; Bustillo-Lecompte et al., 2015, 2016a).

The organic matter concentration in SWW is usually high and the residues are moderately solubilized, leading to a highly polluting effect (Ruiz et al., 1997). They usually contain high levels of organics, pathogenic and non-pathogenic viruses and bacteria, and detergents and disinfectants used for cleaning activities (Debik and Coskun, 2009). The SWW is typically assessed in terms of bulk parameters because of the diverse pollutant loads in the SWW derived from the type and number of animals slaughtered that fluctuate amid the meat industry (Bustillo-Lecompte and Mehrvar, 2015). SWW usually contain high levels of organics and nutrients, expressed as bulk components such as biochemical oxygen demand (BOD), chemical oxygen demand (COD), and total organic carbon (TOC). Thus, SWW is considered detrimental worldwide and on-site treatment would be the best option to treat and disinfect the effluents to be discharged safely into receiving waters (Debik and Coskun, 2009; Wu and Mittal, 2011; Bustillo-Lecompte et al., 2013, 2014; Bustillo-Lecompte and Mehrvar, 2015).

According to Mittal (2006), slaughterhouses in Ontario, Canada, typically discharge the SWW into the municipal sewer system after preliminary treatment. Thus, slaughterhouses commonly pay surcharges, penalties, or fines to dispose their effluents into receiving municipal wastewater treatment plants. Moreover, as of June 2016 there are currently 134 licensed MPPs in Ontario that can process 100-200 animals per month. Approximately 53% of Ontario's slaughterhouses do not treat their wastewater on-site before disposal. Dissolved air flotation (DAF) or aeration is the typical method of preliminary treatment with 16% of Ontario's slaughterhouses using it at their facilities. The rest of slaughterhouses (31%) use passive methods such as lagoons or storage tanks to settle solids (Figure 7.1) (Bustillo-Lecompte and Mehrvar, 2015).

Direct discharge of untreated slaughterhouse effluents to a water body is not practical due to the high organic load of the SWW. Therefore, appropriated disposal and treatment is required. It may also

be stated that in terms of operation and economics, it is beneficial to implement combined processes for the management of slaughterhouse effluents since it couples the benefit of different technologies to improve high strength industrial wastewater treatment (Bustillo-Lecompte et al., 2014).

Although physical, chemical, and biological treatment can be used for SWW degradation, each treatment process has different benefits and drawbacks depending on the SWW characteristics, best available technology, jurisdictions, and regulations. Furthermore, the recovery of valuable by-products from the slaughterhouse effluents is currently focused on the high-quality treatment, the biogas generation, the nutrients, and the fertilizers (Kist et al., 2009; Rajakumar et al., 2011; Barrera et al., 2012; Franke-Whittle and Insam, 2013; Bustillo-Lecompte and Mehrvar, 2015; Bustillo-Lecompte et al., 2013, 2014, 2016a). Hence, the interaction of cross-factor and single-factor effects on the overall process efficiency and biogas yield has not been widely evaluated, rather the microorganism characterization, disinfection, and denitrification have been the focus of studies in recent years (Franke-Whittle and Insam, 2013; Bustillo-Lecompte and Mehrvar, 2015).

On the other hand, research on wastewater treatment commonly includes the study of different contaminants, the effects of operating variables, and the efficiency of the processes. Nevertheless, there are limited studies on the economic information and analysis, reaction mechanisms, and kinetic modeling that may help to estimate the costs of different technologies for scale-up and industrial applications (Durán et al., 2012; Benedetti et al., 2013; Ghafoori et al., 2012, 2013, 2014a).

1.1. Problem statement

Typically, SWWs are treated in anaerobic reactors because of the high organic concentrations (Cao and Mehrvar, 2011). Anaerobic treatment is the preferred biological treatment because of its effectiveness in treating high-strength wastewater such as SWW with less complex equipment requirements. Anaerobically treated effluents require post-treatment to comply with required discharge limits. Although anaerobic treatment is efficient, the complete stabilization of the organic matter is not possible by anaerobic treatment alone; its effluent contains solubilised organic matters, which are more suited for treatment using aerobic processes (Cao and Mehrvar, 2011; Bustillo-Lecompte et al., 2013, 2014). Therefore, aerobic treatment systems are more frequently used in wastewater treatment since they operate at higher rates than conventional anaerobic treatment methods. Taking into account that oxygen requirements and treatment time are directly proportional to an increase in wastewater strength,

aerobic treatment are commonly used for further treatment and nutrient removal following physicochemical and anaerobic treatment methods (Bustillo-Lecompte and Mehrvar, 2015).

Nevertheless, neither anaerobic nor aerobic processes should be employed alone for efficient treatment, since aerobic or anaerobic treatment alone do not produce effluents that comply with effluent discharge limits when treating high organic strength wastewaters. The benefits of the combined anaerobic-aerobic processes include potential resource recovery from the conversion of organic pollutants into biogas with high overall treatment efficiency (Chan et al., 2009).

However, SWWs may contain toxic and non-biodegradable organic substances, which make biological treatment alone insufficient (Oller et al., 2011). Thus, advanced oxidation processes (AOPs) are used to improve the biodegradability of SWW, which may contain non-biodegradable organics and inactivate both pathogenic and non-pathogenic microorganisms without adding additional chemicals to the SWW, avoiding the formation of hazardous by-products. Consequently, AOPs are an attractive alternative to conventional treatment systems and a complementary treatment method to biological processes for the treatment of slaughterhouse effluents (Oller et al., 2011; Cao and Mehrvar, 2011; Barrera et al., 2012; Bustillo-Lecompte and Mehrvar, 2015; Bustillo-Lecompte et al., 2013, 2014, 2016a, 2016b).

Several AOPs have been investigated for SWW treatment, such as ozonation, gamma radiation, and UV/H₂O₂ (Wu and Doan, 2005; Melo et al., 2008; De Sena et al., 2009; Luiz et al., 2009; Cao and Mehrvar, 2011; Barrera et al., 2012; Bustillo-Lecompte et al., 2014; Bustillo-Lecompte et al., 2015). However, the UV/H₂O₂ process has been found to be more efficient for SWW treatment. The UV/H₂O₂ process is five times faster in inactivation and inhibition of microorganisms as well as in degrading aromatic compounds than other AOP technologies. Removal efficiencies of up to 97, 95, and 75% could be achieved by the UV/H₂O₂ process for COD, BOD, and TOC, respectively (De Sena et al., 2009; Luiz et al., 2009; Cao and Mehrvar, 2011; Wu and Mittal, 2011; Barrera et al., 2012; Bustillo-Lecompte et al., 2013, 2014). Thus, AOPs could be considered to enhance the SWW quality for water reuse purposes.

The combined processes for wastewater treatment can be considered to be multifactor systems due to the interaction of different parameters on the overall process efficiency including organics concentration, reaction time, pH, light source intensity, oxidant concentration, output power, among

others, which have not been widely investigated. Therefore, the optimization of such systems requires considering both single-factor and cross-factor effects through a design of experiments (DOE) to identify the factors that influence the multivariable system while overcoming the limitations of traditional experimental methods in terms of the number of experimental trials, time, and materials (Ghafoori et al., 2012, 2014a, 2015; Bustillo-Lecompte et al., 2016a, 2016b). On the other hand, the available information on the reaction mechanisms and detailed kinetic modeling of combined biological and AOP systems involving all free radicals and molecular species for the degradation of SWW is limited (Ghafoori et al., 2012; Bustillo-Lecompte and Mehrvar, 2015).

The optimization of parameters by conventional methods needs time, materials, and a large number of experiments. On the other hand, parameters such as H₂O₂ residuals, known to be toxic to microorganisms in biological post-treatment, and recycle ratio, known as the ratio of recycle flow rate to the main feed flow rate, are not widely investigated. Moreover, conventional methods fail to consider the combined effects of all the factors involved. Therefore, a DOE is used to overcome the limitations of conventional methods and consequently optimize the factors involved. Conversely, response surface methodology (RSM) has been recognized to be statistically reliable to analyze multifactor systems in chemical treatment processes. RSM considers cross-factor interactions to attain optimal responses using the minimum number of experiments (Ghafoori et al., 2012, 2014a, 2015; Bustillo-Lecompte et al., 2016a; Šereš et al., 2016).

As a result, adopting combined processes for SWW treatment is considered operationally and economically advantageous because it incorporates and optimizes the advantages of different technologies to achieve high-quality effluents from industrial and high-strength wastewaters (Mehrvar and Tabrizi, 2006; De Nardi et al., 2011; Bustillo-Lecompte et al., 2013, 2014; Mowla et al., 2014; Bustillo-Lecompte and Mehrvar, 2015). Furthermore, considering the eventual reduction in operation and maintenance costs, high removal efficiency requirements, potential energy recovery from biogas production, and enhanced quality for water reuse purposes, combined biological processes and AOP systems are recommended for SWW treatment provided that the system be optimized at an appropriate residence time in each reactor (Tabrizi and Mehrvar, 2004; Oller et al., 2011; Bustillo-Lecompte and Mehrvar, 2015).

1.2. Objectives and scope of the project

The purpose of this study is to evaluate the current wastewater treatment technologies used in the meat processing sector in Ontario; thus, to assess possible alternatives in order to minimize the impact of the discharge of these wastewaters to the environment. In this study, the information on current meat processing plants (MPPs) in Ontario, including characteristics of the actual wastewater and type of treatment/storage/disposal used is examined. This study required sampling of an actual slaughterhouse wastewater (SWW), experimental work to assess the overall removal of organics and nutrients, optimization of reactors and systems for SWW treatment, potential energy recovery from biological processes, modeling, and cost-efficiency analysis for industry applications. This study is highly beneficial as a contribution to the advancement of knowledge due to the lack of information and enforcement on adequate treatment of SWWs. In summary, the objectives of the present study are:

1. To perform an exhaustive review on SWW characteristics, treatment, and management in the meat processing industry;
2. To evaluate the performance of combined biological and advanced oxidation processes for the treatment of an actual slaughterhouse wastewater.
3. To evaluate the effects of different variables on the overall treatment of an actual slaughterhouse wastewater, including influent concentration of organics, oxidant dosage, feed flow rate, pH, and their interaction on the overall treatment efficiency, effluent pollutant residuals, and potential energy recovery;
4. To describe common degradation mechanisms and predict the percentual TOC removal as the output variable with time in the optimized combined processes for the actual SWW treatment;
5. To evaluate the effect of a recycle stream in the UV/H₂O₂ process on the TOC removal and H₂O₂ residual in the effluent.
6. To optimize operating conditions of the reactors for SWW treatment, overall treatment time, and energy consumption
7. To evaluate the operating costs of treating SWW for individual processes and the proposed ABR–AS–UV/H₂O₂ system for TOC removal using a cost-effectiveness analysis (CEA) by minimizing the incurred treatment costs, the electrical energy consumption, and the retention time required for the efficient treatment of actual slaughterhouse effluents and potential energy recovery.

1.3. Dissertation outline

This dissertation is written in a manuscript-based format such that the chapters can be read independently. The materials and methods used in the present dissertation are presented in Chapter 2. The reader might find a few repetitions in the subsequent chapters due to the format of this dissertation. Nevertheless, all chapters were integrated into a logical progression from chapter to chapter to create a unified and consistent dissertation. The following publications resulted from this PhD work and are listed in the order of presentation in this dissertation:

1. **C. Bustillo Lecompte**; and M. Mehrvar; (2015) *Slaughterhouse wastewater characteristics, treatment, and management in the meat processing industry: a review on trends and advances*. Journal of Environmental Management 161, pp. 287-302. (**Chapter 3**).
2. **C. Bustillo Lecompte**; M. Mehrvar and E. Quiñones Bolaños (2014) *Cost-Effectiveness Analysis of TOC Removal from Slaughterhouse Wastewater using Combined Anaerobic-Aerobic and UV/H₂O₂ Processes*. Journal of Environmental Management 134, pp. 145-152. (**Chapter 4**).
3. **C. Bustillo Lecompte**; and M. Mehrvar; (2016) *Treatment of actual slaughterhouse wastewater by combined anaerobic-aerobic processes for biogas generation and removal of organics and nutrients: an optimization study towards a cleaner production in the meat processing industry*. Journal of Cleaner Production. (Submitted). (**Chapter 5**).
4. **C. Bustillo Lecompte**; S. Ghafoori; and M. Mehrvar (2016) *Photochemical degradation of an actual slaughterhouse wastewater by continuous UV/H₂O₂ photoreactor with recycle*. Journal of Environmental Chemical Engineering 4 (1), pp. 719-732. (**Chapter 6**).
5. **C. Bustillo Lecompte**; M. Mehrvar and E. Quiñones Bolaños (2016) *Slaughterhouse wastewater characterization and treatment: an economic and public health necessity of the meat processing industry in Ontario, Canada*. Journal of Geoscience and Environment Protection 4, pp. 175-186. (**Chapter 7**).
6. **C. Bustillo Lecompte**; and M. Mehrvar; (2016) *Treatment of actual slaughterhouse wastewater by integrating biological and advanced oxidation processes: modeling, optimization, and cost-effectiveness analysis*. Journal of Environmental Management. (In Press). (**Chapter 8**).

Finally, Chapter 9 outlines the main findings and conclusions of this study as the original contribution of the dissertation to the advancement of knowledge in the research area of industrial wastewater treatment, as well as the recommendations for future work. Finally, some supplementary materials are provided in Appendix S to complement chapters presented in this dissertation.

1.4. Contributions of co-authors

The principal author, *Ciro Fernando Bustillo-Lecompte*, wrote all Chapters presented in this dissertation. The principal author was also in charge of and responsible for the design and identification of the research undertaken, performed analysis on all samples, interpreted and analysed data and questionnaires, and prepared manuscripts for submission to refereed journals.

Chapters 3, 4, 5, 6, 7 and 8 have been submitted to refereed journals and were co-authored by *Dr. Mehrab Mehrvar*, the sole dissertation supervisor, who guided the development and the progress of the project, helped in data interpretation and manuscript revisions and evaluation by providing editorial and technical advice, and acted as corresponding author. *Dr. Edgar Quiñones-Bolaños*, Professor of Environmental Engineering of the University of Cartagena, Cartagena de Indias, Colombia, provided assistance in data analysis to portions of the work performed in Chapters 4 and 7, and is listed as a co-author accordingly. Finally, *Dr. Samira Ghafoori*, faculty member of the Australian College of Kuwait, Mishrif, Kuwait City, Kuwait, provided assistance in data analysis to portions of the work performed in Chapter 6, and is listed as a co-author accordingly.

CHAPTER 2

MATERIALS AND METHODS

2.1. Introduction

This study aims to identify the most recent trends and advances in meat processing effluent management and common practices in slaughterhouse wastewater (SWW) treatment and characteristics. This study is also focused on determining the performance and the treatment ability of the ABR, the aerobic AS, and the UV/H₂O₂ processes, as well as their combination for the treatment of actual SWW. Therefore, this chapter presents the main materials and methods used to carry out this project.

2.2. Materials

2.2.1. Actual slaughterhouse wastewater samples

Actual SWW sources may contain feces, urine, blood, lint, fat, carcasses, and non-digested food from slaughtered animals, production leftovers, and cleaning of the facilities (Bustillo-Lecompte et al., 2013; Bustillo-Lecompte and Mehrvar, 2015). Therefore, all solids and large particles were separated from the wastewater using a mesh with a 4.00 mm sieve size. Actual SWW samples were taken from selected provincially licensed meat processing plants directly from their source in Ontario, Canada, at different times of the study (OMAFRA, 2014, 2015a, 2015b). Although SWW composition varies according to the industrial process and water demand, they usually contain high levels of organics and nutrients, typically measured as biochemical oxygen demand (BOD), chemical oxygen demand (COD), total organic carbon (TOC), total suspended solids (TSS), total nitrogen (TN), and phosphorus (TP). Thus, homogenized actual SWW samples had an average TOC concentration of 862 mg/L. Table 2.1 shows the overall SWW characteristics from the selected provincially licensed meat processing plants (Bustillo-Lecompte and Mehrvar, 2015, 2016a, 2016b). The SWW features and common ranges are listed as BOD, COD, TOC, TSS, TN, and pH. Ten sample sites were used depending on the TOC range of each stage of the study. Distilled water (DW) was used to dilute SWW samples in order to adjust the influent TOC concentrations to different DOE levels accordingly.

Table 2.1. Characteristics of the actual slaughterhouse wastewater from selected provincially licensed meat processing plants along with study range values and detection limits.

Parameter	Range	Mean	Detection limits
BOD (mg/L)	37.95–8,231	2,649	0.000-10,000
COD (mg/L)	76.43–14,256	5,577	0.000-15,000
Color (mg/L Pt scale)	178.0-391.0	289.0	0.000-500.00
TN (mg/L)	6.120–841.0	427.0	0.100-25,000
TOC (mg/L)	10.51–1,718	862.1	0.100-25,000
TP (mg/L)	0.143–200.0	42.81	0.020-125.00
TSS (mg/L)	0.287–9,938	3,092	0.000-750.00
Turbidity (FAU ^a)	271.0-279.0	275.0	0.000-1,000.0
pH	4.90–8.10	6.95	4.0-10

^a FAU, formazin attenuation units.

2.2.2. Chemicals and reagents

A 30% w/w hydrogen peroxide solution was used as the AOP oxidant and purchased from Sigma-Aldrich (Oakville, ON), whereas NaOH (50% w/w) and H₂SO₄ (98% w/w) were obtained from EMD Millipore (Etobicoke, ON) for pH adjustment. The H₂O₂ residual was measured using the copper-neocuproine method (Baga et al., 1988; Kosaka et al., 1998; Brandhuber and Korshin, 2009; Hamad et al., 2014; Bustillo-Lecompte et al., 2016a). The reagents and materials required by this method were neocuproine (2,9-dimethyl-1,10-phenanthroline) purchased from Sigma-Aldrich (Oakville, ON), ethanol was purchased from BDH (Mississauga, ON), copper (II) sulfate pentahydrate, K₂HPO₄, and NaH₂PO₄ were purchased from Sigma-Aldrich (Oakville, ON). All chemicals and reagents were used as received.

2.2.3. Anaerobic and aerobic inoculum

The anaerobic and aerobic sludge seeds were obtained from the Ashbridges Bay Wastewater Treatment Plant, a municipal wastewater treatment plant in Toronto, Ontario. The sludge samples were transported in 20-L closed containers and used as received. The inoculum was acclimatized in eight weeks by feeding the actual slaughterhouse wastewater (SWW) continuously into the bioreactors using a peristaltic pump at a constant flow rate of 75 mL/min while gradually increasing its concentration on biweekly basis from 25, 50, and 75% to 100% of the actual SWW.

2.3. Experimental setup

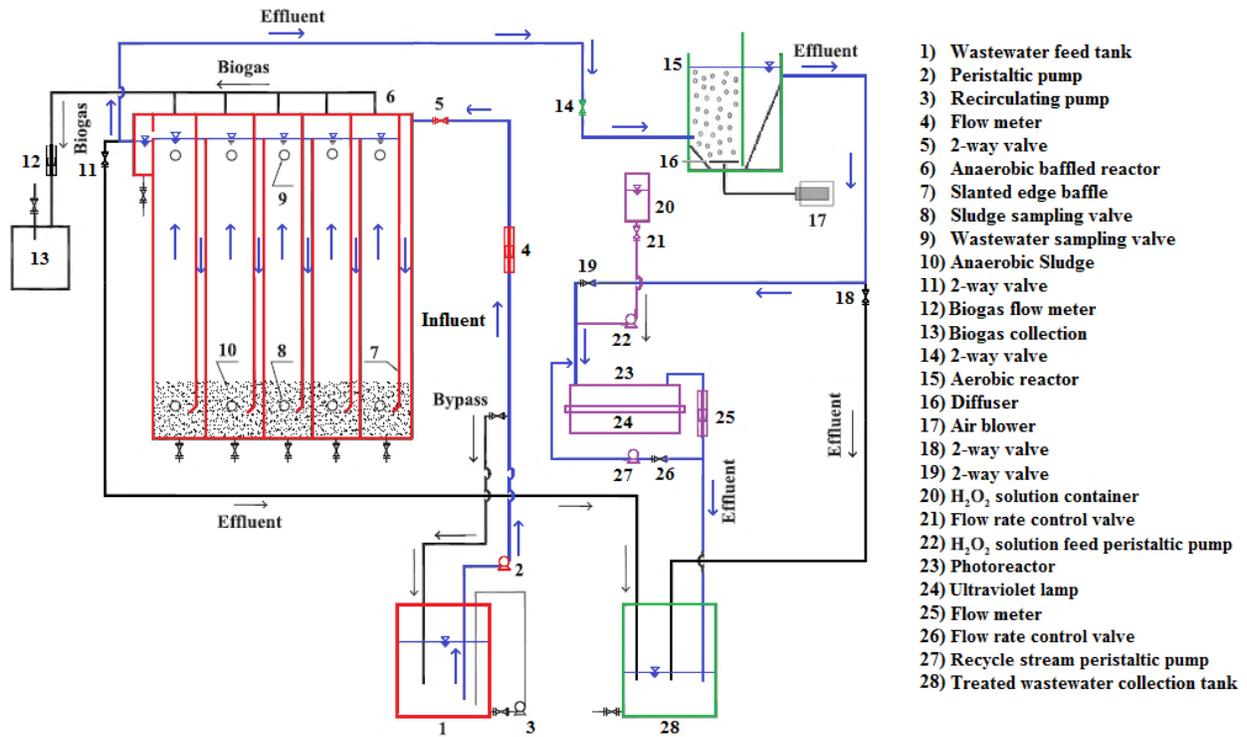
An anaerobic baffled reactor (ABR), an aerobic activated sludge (AS) reactor, and a UV/H₂O₂ photoreactor, were operated in continuous mode and used individually and as a combined system at the laboratory scale for SWW treatment. The schematic diagram of the experimental setup for the combined ABR–AS–UV/H₂O₂ processes is illustrated in Figure 2.1 while Figure 2.2 shows the laboratory scale experimental setup.

The combined biological and advanced oxidation system consisted of three reactors (Figure 2.1). First, a 36-L ABR with five chambers, individual headspaces, and biogas collection piping was used for anaerobic treatment (Figure 2.1b). In the ABR, a 45° slanted-edge baffle within each ABR chamber permitted the down- and up-flow course of the actual SWW, providing effective mixing and contact time between the SWW and the biomass. Second, a 12.65-L AS bioreactor was used for aerobic treatment (Figure 2.1c). The air flow rate in the AS bioreactor was supplied using an air diffuser and was set to 1.2–2.0 L/min by a control valve with air flow meter to guarantee nitrifying bacteria growth and dissolved oxygen (DO) concentrations over 2.0 mg/L. Finally, a 1.35-L photoreactor with recycle and uniform light distribution was used as the AOP (Figure 2.1d). The stainless steel cylindrical photoreactor (Barrier SL-1S – Siemens Inc., Markham, ON) had an external diameter of 8 cm and a length of 34 cm and a 2.5 cm diameter UV-C lamp was inserted into the center of the photoreactor with an output power of 6 W and a 254 nm wavelength. A quartz sleeve was used to protect the lamp from fouling and maintain a uniform UV-C radiation emission.

2.4. Experimental procedure

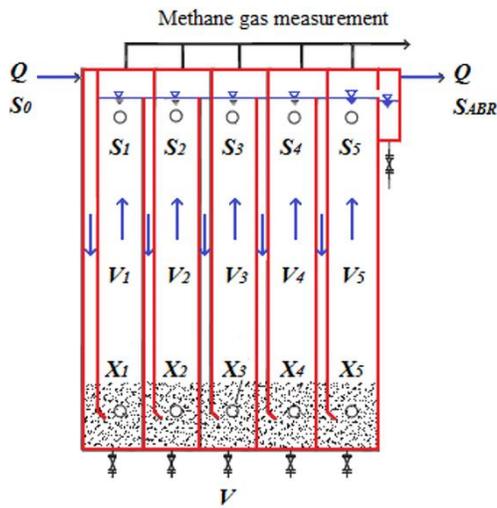
2.4.1. Acclimatization of the inoculum

Anaerobic and aerobic sludge seeds were loaded into the anaerobic and aerobic bioreactors, respectively. Twelve liters of an anaerobic sludge seed (38000 mg/L), using 2.4 L of the inoculum for each of the five chambers of the ABR (1/3 of the total working volume), and 5 L of an aerobic sludge seed (3000 mg/L) were loaded into the anaerobic and aerobic bioreactors, respectively. The inoculum was acclimatized in eight weeks by feeding the actual SWW continuously into the bioreactors using a peristaltic pump at a constant flow rate of 75 mL/min.

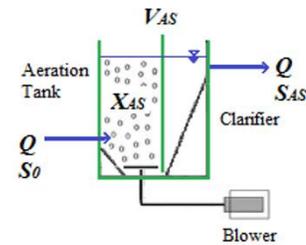


- 1) Wastewater feed tank
- 2) Peristaltic pump
- 3) Recirculating pump
- 4) Flow meter
- 5) 2-way valve
- 6) Anaerobic baffled reactor
- 7) Slanted edge baffle
- 8) Sludge sampling valve
- 9) Wastewater sampling valve
- 10) Anaerobic Sludge
- 11) 2-way valve
- 12) Biogas flow meter
- 13) Biogas collection
- 14) 2-way valve
- 15) Aerobic reactor
- 16) Diffuser
- 17) Air blower
- 18) 2-way valve
- 19) 2-way valve
- 20) H₂O₂ solution container
- 21) Flow rate control valve
- 22) H₂O₂ solution feed peristaltic pump
- 23) Photoreactor
- 24) Ultraviolet lamp
- 25) Flow meter
- 26) Flow rate control valve
- 27) Recycle stream peristaltic pump
- 28) Treated wastewater collection tank

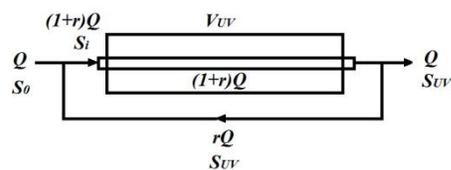
(a) Combined anaerobic-aerobic processes for the treatment of SWW



(b) anaerobic baffled reactor



(c) aerobic activated sludge bioreactor



(d) UV/H₂O₂ photoreactor with recycle

Figure 2.1. Schematic diagram of (a) the combined anaerobic-aerobic processes for the treatment of SWW and the individual processes (b) anaerobic baffled reactor, (c) aerobic activated sludge bioreactor, and (d) UV/H₂O₂ photoreactor with recycle.

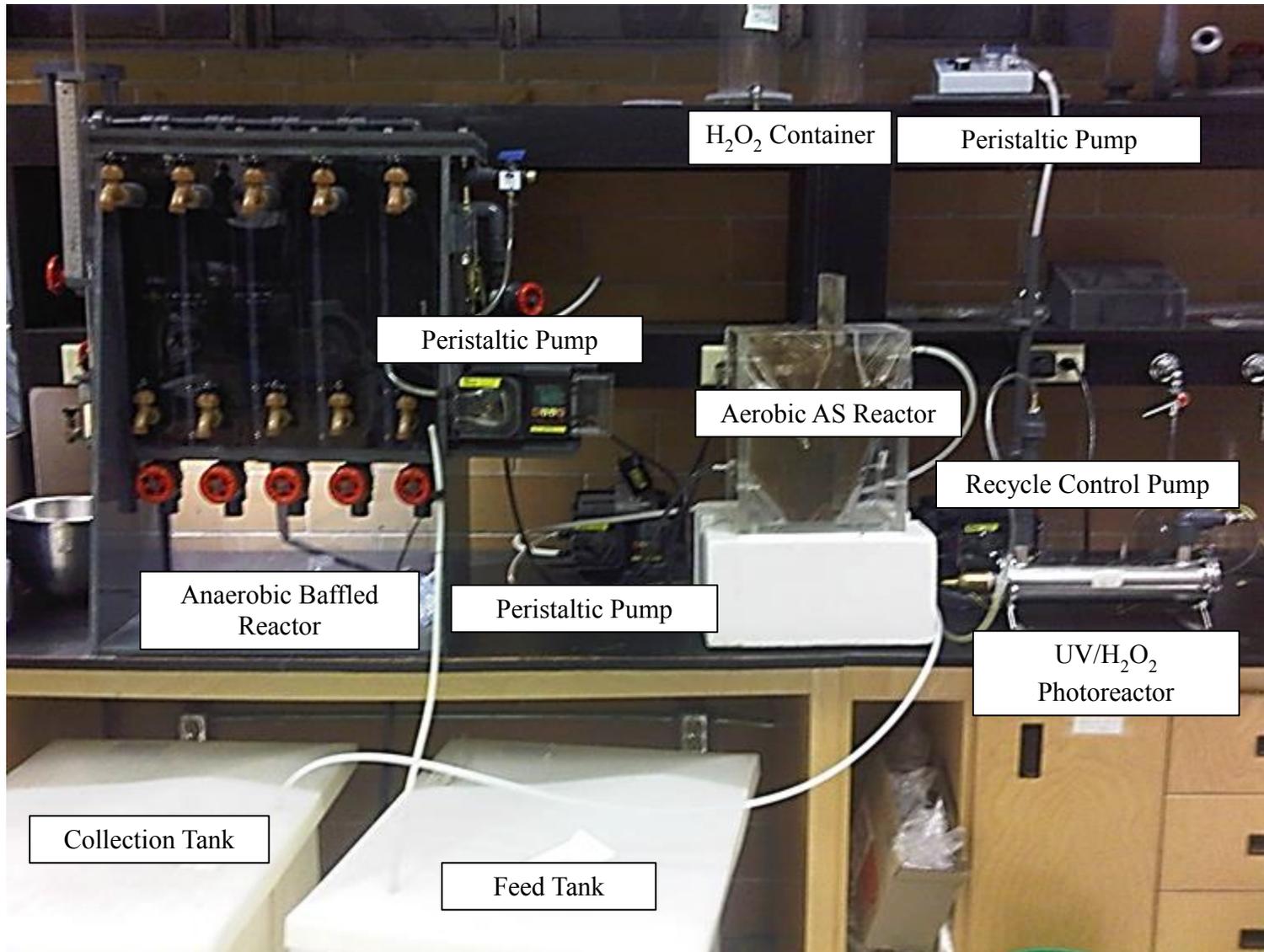


Figure 2.2. Laboratory scale combined ABR-AS-UV/H₂O₂ system with recycle.

During the 60-days acclimatization period, the influent substrate concentration was gradually increased biweekly from 25, 50, and 75% to 100% of the actual SWW. Biomass growth was monitored by collecting samples from each compartment of both ABR and AS bioreactors during the acclimatization period by measuring the concentrations of both total suspended solids (TSS) and volatile suspended solids (VSS).

2.4.2. ABR process

After the 60-day acclimatization period, the ABR was run alone using different influent concentrations of the actual SWW and various flow rates. Operating conditions were in the range of 50–1650 mgTOC/L, 15–135 mL/min, pH from 3 to 11, and HRT from 4.5 to 40 h. The SWW was homogenized and fed continuously from a feed tank using a peristaltic pump (Blue-White Industries Ltd. Flexflo A-100NV). The actual SWW was passed through an acrylic flow meter (Omega FL-2018) in order to measure the flow rate. The flow was then directed to the ABR using the 3-way valve and flowed downwards and upwards within the five compartments of the ABR. Those compartments contained an anaerobic sludge layer where the biological degradation occurs. Each compartment had a sludge sampling port, located 10 cm from the base of the ABR and 4 cm from the side of the 45° slanted edge baffle, to measure TSS and VSS. The actual SWW sampling ports were located 40 cm from the base of the ABR and 4 cm from the side of the 45° slanted edge baffle.

Samples during treatment were taken by gravity from every compartment. When collecting samples, the first 5 mL were eliminated to avoid the effect of the sampling ports; then, volumes of 10 mL were collected from each sampling port. Finally, the treated effluent was either discharged into the collection tank or flowed into the aerobic AS bioreactor for post-treatment. All experiments were repeated in triplicates, and the average values were reported.

2.4.3. Aerobic AS process

The aerobic AS process was run as an individual process after the acclimatization period using different influent concentrations and various flow rates. The operating conditions for the AS bioreactor were similar to those in the ABR and HRTs varied from 1.6 to 14 h.

The actual SWW was homogenized and fed continuously from a feed tank using a peristaltic pump. The actual SWW was passed through an acrylic flow meter. The flow was then directed to the AS

reactor using the 3-way valve and flowed into the aeration tank, where oxygen was introduced by a diffuser at a constant air flow rate of 2 L/min followed by a clarifier. Samples of 10 mL were taken from the aeration tank and the clarifier. The treated effluent was either discharged into the collection tank or flowed into the UV/H₂O₂ photoreactor for post-treatment. All experiments were repeated in triplicates, and the average values were reported.

2.4.4. UV/H₂O₂ process

The aerobic UV/H₂O₂ process was run alone using different influent concentrations of the actual SWW and various flow rates. Operating conditions were in the range of 10–626 mgTOC/L, 100–1500 mgH₂O₂/L, 15–135 mL/min, pH from 3 to 11, and HRT from 0.2 to 1.5 h. The following procedure was implemented to carry out each experiment for quality control:

- 1) The UV lamp was switched on for 30 min prior to the start of each experiment to guarantee light intensity stabilization within the photoreactor and to remove any possible background materials.
- 2) SWW samples were filtered to separate the liquid portion of the wastewater from the solids.
- 3) Filtered SWW samples were then diluted to reach the desired TOC concentration and guarantee the accuracy of the feed concentration value in a 6-L solution (i.e. an actual slaughterhouse wastewater sample with a concentration of 26.42 mg/L was diluted to 25.00 mg/L).
- 4) The SWW solution with the desired TOC concentration was fed to the photoreactor by a variable speed peristaltic pump to control and adjust the flow rate.
- 5) An adequate H₂O₂ concentration was calculated based on the material balance for each experiment.
- 6) The H₂O₂ solution was also fed to the system by a secondary variable speed peristaltic pump at the time the SWW solution started to be fed to the photoreactor.
- 7) A recycle stream was controlled using the third variable speed peristaltic pump to adjust the flow rate to the desired recycle ratio.
- 8) Effluent samples were taken at 15-min intervals until the system reached steady state conditions.

An experiment without UV irradiation, called the dark experiment, was also conducted to evaluate the possible adsorption of organic compounds on the UV photoreactor walls. All experiments were repeated in triplicates, and the average values were reported.

2.4.5. Combined anaerobic-aerobic system

After the acclimatization period, the combined ABR–AS system was run using different influent concentrations of the actual SWW and various flow rates. Operating conditions were in the range of 50–1650 mgTOC/L, 15–135 mL/min, pH from 3 to 11, and HRT from 6 to 54 h. The following procedure was used in performing each experiment in the combined ABR–AS processes for quality control:

- 1) For every experiment, six SWW samples of 20-L were collected from MPPs and filtered on-site to separate the liquid from the solid portion of the SWW.
- 2) Filtered SWW samples were then diluted to reach the desired TOC concentration of the feed in a 120-L solution.
- 3) A 1 N solution of sulfuric acid (H_2SO_4) and a 50% solution of sodium hydroxide (NaOH) were used to adjust the pH.
- 4) The SWW solution with the desired TOC concentration and pH was fed into the combined ABR–AS processes by a variable speed peristaltic pump to control and adjust the flow rate.
- 5) Effluent samples were taken at 3 h intervals until the system reached steady state conditions.
- 6) All experiments were repeated in triplicates, and the average values were reported.

2.4.6. Combined anaerobic-aerobic and UV/H₂O₂ system

After the acclimatization period, experiments for combined processes of the ABR, the aerobic AS, and UV/H₂O₂ were conducted using different influent concentrations of the actual SWW and various flow rates. Operating conditions were in the range of 50–1650 mgTOC/L, 15–135 mL/min, pH from 3 to 11, and HRT from 6.2 to 55.6 h. The following procedure was used during the performance of each experiment in the combined ABR–AS–UV/H₂O₂ system for quality control:

- 1) For every experiment, six SWW samples of 20-L were collected from MPPs and filtered on-site to separate the liquid from the solid portion of the SWW.
- 2) Filtered SWW samples were diluted to reach the desired TOC concentration of the feed in a 120-L solution.
- 3) Sulfuric acid (H_2SO_4) solution at 98% and sodium hydroxide (NaOH) solution at 50% w/w were used to adjust the pH.
- 4) The SWW solution with the desired TOC concentration and pH was fed to the combined ABR–AS–UV/H₂O₂ system by a variable speed peristaltic pump to control and adjust the flow rate.

- 5) The required H_2O_2 concentration was calculated based on the material balance for each experiment, by which the H_2O_2 solution flow rate to the photoreactor was adjusted and fed by a secondary variable speed peristaltic pump.
- 6) In the photoreactor, there was a recycle stream, for which a third variable speed peristaltic pump was used to adjust the flow rate to the desired recycle ratio.
- 7) Effluent samples were taken at 3-h intervals until the system reached steady state conditions.
- 8) All experiments were repeated in triplicates, and the average values were reported.

2.5. Research methods

A mixed methods approach was used in this dissertation. Figure 2.3 shows the diagram representation of the research methods used in this study to determine the types of wastewater treatment technologies currently used in the meat-processing sector in Ontario, to assess possible alternatives in order to minimize the impact of the discharge of the slaughterhouse effluents to the environment and the overall treatment costs. Therefore, the study was divided into two phases, theoretical and experimental as shown in Figure 2.3.

2.5.1. Theoretical phase

The objectives, background research, scope and boundaries are depicted in a preliminary stage. The sampling of sludge and the actual SWW categories were introduced in the theoretical stage because their determination was based on the analysis of the information collected from the facilities through questionnaires and a literature review (Bustillo-Lecompte and Mehrvar, 2015). Furthermore, the information about the meat processing industry in Ontario was collected using questionnaires sent to current meat processing plants (MPPs) in Ontario (Appendix F), as well as conducting literature review on SWW characteristics. An approval from the research ethics board and a renewal (Appendix G) were obtained to conduct the questionnaires distributed along with a consent form (Appendix H). The questionnaire addressed the characteristics of the actual SWW, type of animals being processed, the number of animals slaughtered per year, and the type of treatment/storage/disposal used in those MPPs and served as basis for the literature review shown in Chapter 3 of this dissertation (Bustillo-Lecompte and Mehrvar, 2015).

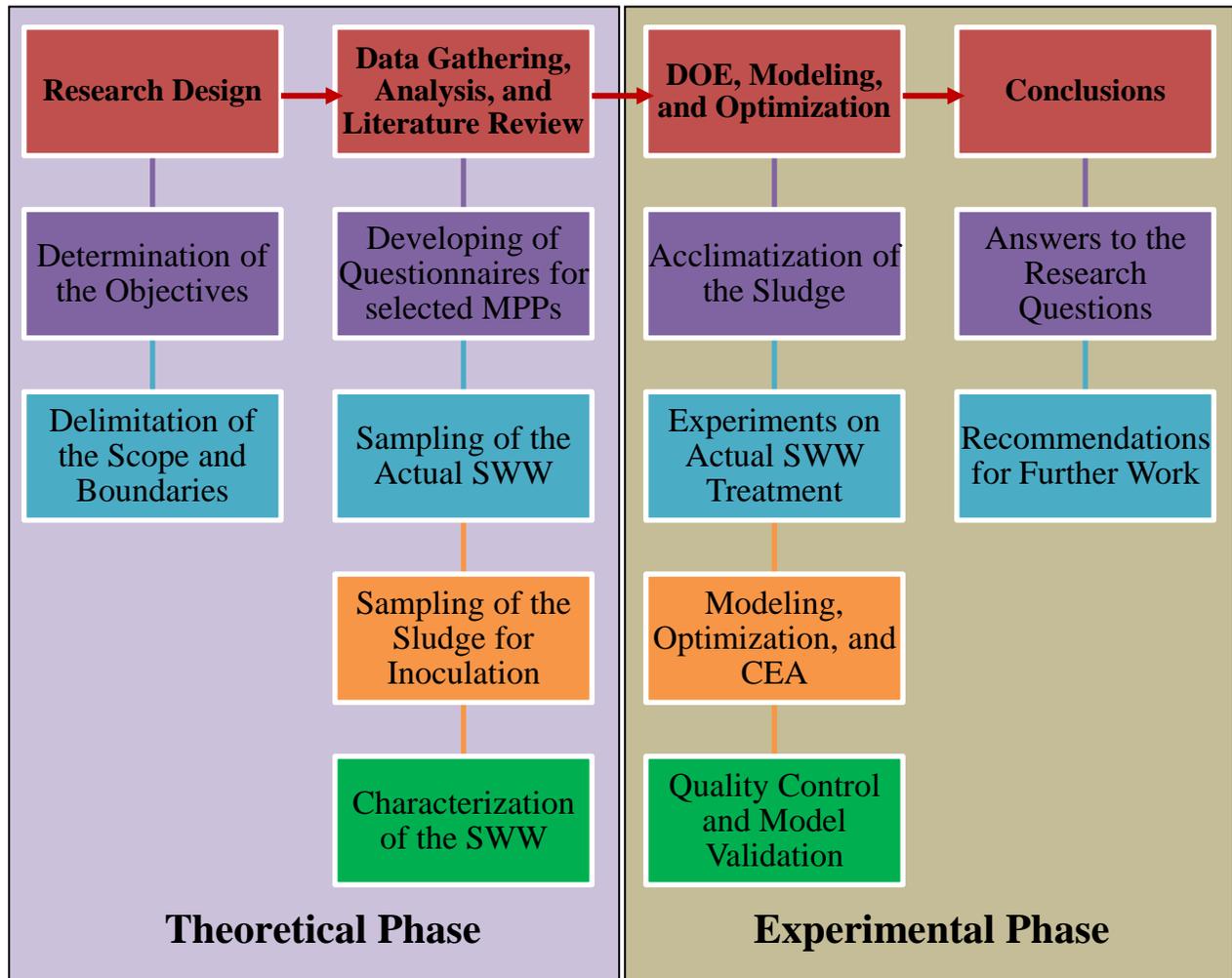


Figure 2.3. Diagram representation of the research methods used in this study.

2.5.2. Experimental phase

The experimental phase was essential to accomplishing the objectives of this study. This experimental phase was focused on the sampling of actual SWW and further experiments for the removal of organics and nutrients, CH₄ production, and overall treatment time and costs minimization. Thus, current technologies costs and efficiencies were examined via cost-effectiveness analysis (CEA), followed by the optimization of reactors and systems for SWW treatment, modeling, and a final CEA at optimum conditions. Chapters 4 to 8 provide an appraisal of the experimental phase results (Bustillo-Lecompte et al. 2014, 2016a, 2016b; Bustillo-Lecompte and Mehrvar, 2016a, 2016b).

2.6. Experimental design, modeling, and optimization

DOE is used to overcome the limitations of conventional experimental methods, in terms of time, materials, and the number of experimental trials, to optimize the factors involved in the treatment process. The DOE permits the optimization of all parameters and consider the combined effects of all the factors involved. Besides, the response surface methodology (RSM) has been recognized to be statistically reliable to analyze multifactor systems in biological and chemical treatment processes. RSM considers cross-factor interactions to attain optimal responses using the minimum number of experiments (Ghafoori et al., 2012, 2014a, 2015; Bustillo-Lecompte et al., 2016a; Šereš et al., 2016).

2.6.1. Response Surface Methodology

Response surface methodology (RSM) is a combination of mathematical and statistical techniques that is an effective tool for developing, improving, and optimizing different processes. In addition to the significant applications in the design, development, and formulation of new products, it could be used in the improvement of existing product designs. The most important application of RSM is in industrial processes, especially where different input variables or factors influence some performance measure or quality characteristic of the process. This performance measure or quality characteristic of the process is called response. In many real applications of RSM, there is more than one response. The input variable or the factors are called independent variables and the typical designs are either a Box-Behnken Design (BBD) or a Central Composite Design (CCD), depending on the number of factors and their levels. In optimization, the responses could be coupled to selected variables by linear or quadratic models. A quadratic model equation for predicting the response functions (organic degradation and TOC removal efficiencies) could be developed using a second order polynomial expression as follows (Ghafoori et al.,

2012, 2014a, 2015; Bustillo-Lecompte et al., 2016a, 2016b; Bustillo-Lecompte and Mehrvar, 2016a, 2016b):

$$Y_i = \beta_o + \sum_{i=1}^k \beta_i X_i + \sum_{i=1}^k \beta_{ii} X_i^2 + \sum_{i=1}^{k-1} \sum_{j=2}^k \beta_{ij} X_i X_j + c \quad (2.1)$$

where β_o , β_i , β_{ii} , and β_{ij} are the constant, linear, quadratic, and cross-factor interaction coefficients, respectively; X_i and X_j represent the independent variables; Y_i is the predicted response; and k and c are the number of factors and the residual term, respectively.

On the other hand, to obtain a simultaneous objective function that represents the geometric mean of all transformed responses, the desirability multiple response method was used to combine the desirable ranges for each response as shown in Equation (2.2) (Myers et al., 2004; Bustillo-Lecompte et al., 2016a, 2016b; Bustillo-Lecompte and Mehrvar, 2016a, 2016b):

$$D = (d_1 \times d_2 \times d_3 \times d_4 \dots \times d_n)^{1/n} = \left(\prod_{i=1}^n d_i \right)^{1/n} \quad (2.2)$$

where D , d_i , and n are the desirability objective function, each individual response range, and the number of responses, respectively. For a simultaneous optimization, each response requires low and high values for the optimization. Otherwise, if any response is found outside of its desirability range, the overall desirability becomes equal to zero.

2.6.2. Validation of model adequacy

Generally, in RSM, it is always essential to: (i) validate the fitted model to ensure that it provides an adequate approximation to the true system, and (ii) verify that none of the least square regression assumptions is violated. Proceeding with exploration and optimization of a fitted response surface likely gives misleading results unless the model provides a satisfactory fit. The residual from the least square fit, which refers to the difference between the model prediction and the observation, is a good indicator for the model adequacy. A validation of the normality assumption is made by constructing a normal probability plot of the residuals. If the residual plot lies on the straight line, then the normality assumption is satisfied. Another plot to validate the model adequacy is the plot of residuals over the predicted

response. If the residuals scatter randomly on the display in form of a "gunshot pattern", the model is adequate (Mehrvar et al., 2000). However, the scaled residuals are often more preferable as they convey more information than the ordinary least square residuals. One of the scaled residuals more widely used is the studentized residual. The studentized residuals are found by dividing the residuals by their standard deviations. If the points scatter randomly between the outlier detection limit of -3 and +3, the model adequacy is satisfied.

2.7. Cost-effectiveness analysis

A CEA is an economic analysis that compares the relative costs and effects of two or more courses of action. Thus, in order to gain the maximum benefit from the combined system, the residence time in each reactor and the treatment efficiency should be optimized. Therefore, three objective functions were defined as constrains, including the individual retention time minimization, the total power consumption minimization, and the overall treatment cost minimization. In combined processes, there is a relationship between the HRT and the volume of each reactor. Considering the flow rate of the H₂O₂ negligible, this relationship can be represented by Equation (2.9).

$$\frac{V_{ABR}}{t_{ABR}} = \frac{V_{AS}}{t_{AS}} = \frac{V_{UV}}{t_{UV}} \quad (2.9)$$

where,

V_{ABR} = volume of the ABR (L);

V_{AS} = volume of the aerobic AS reactor (L);

V_{UV} = volume of the UV photoreactor (L);

t_{ABR} = hydraulic retention time of the ABR process (h);

t_{AS} = hydraulic retention time of the aerobic AS process (h); and

t_{UV} = hydraulic retention time of the UV/H₂O₂ process (h).

2.8. Analytical techniques and equipment for sample analysis

Different variables of the SWW were measured, including DO, temperature, and pH, measured daily by a DO meter (YSI 58 Dissolved Oxygen Meter, Yellow Springs, OH) and a pH meter (Thermo Scientific Orion 230A+, Ottawa, ON), respectively. TOC and TN measured automatically by a TOC/TN analyzer (Teledyne Tekmar Apollo 9000 Combustion, Mason, OH). COD and TP were measured by

colorimetry method (Orbeco-Hellige MC500 Multi-Parameter Colorimeter, Sarasota, FL). BOD was measured by respirometry assays (Bioscience BI-2000 Electrolytic, Allentown, PA). The concentrations of TSS and VSS were measured according to the *Standard Methods* of the American Public Health Association (APHA, 1998, 2012). The H₂O₂ residuals were measured with a UV-Visible Spectrophotometer (Ultrospec 1100 pro – Amersham Biosciences, Amersham, UK) at 454 nm using neocuproine and copper (Bustillo-Lecompte et al., 2016a). Three replicates were made for each analytical measurement and the average values were reported along with the standard deviation. The details of each analytical technique are explained in the following sections.

2.8.1. Dissolved oxygen (DO)

The DO of influent and effluent samples of the SWW was measured by a dissolved oxygen meter (YSI 58 Dissolved Oxygen Meter, Yellow Springs, OH) equipped with a BOD bottle probe (YSI 5905 BOD Probe). The DO meter was calibrated using air-saturated water, obtained by aerating water for at least 15 min at a constant temperature, using the calibration by temperature measurement function of the DO meter.

2.8.2. Temperature and pH

Temperature and pH of influent and effluent samples of the SWW were measured by a portable pH meter (Thermo Scientific Orion 230A+, Ottawa, ON). This instrument has a pH resolution of 0.01, a pH accuracy of ± 0.02 , a temperature range of -5.0 to 105.0°C, a temperature resolution of 0.1°C, and a temperature accuracy of $\pm 1.0^\circ\text{C}$. The pH meter was calibrated using either a pH 4.01 and 7.00 buffer solution or a 7.00 and 10.01 buffer solution, depending on the expected sample range, at room temperature.

2.8.3. Total suspended solids (TSS) and volatile suspended solids (VSS)

TSS and VSS of the SWW effluent of each reactor, and the anaerobic and aerobic sludge were measured according to sections 2540D and 2540E of *Standard Methods* (APHA, 1998, 2012) to observe the growth of microorganisms in the reactors or to assess whether the effluent solids concentrations reached an adequate disposal level. For the TSS values, filter papers and aluminum weighing dishes were dried in an oven (Binder Oven FED 53) at 105°C for 1 h. Well-mixed sludge samples of 5 to 10 mL were separately filtered by weighed filter papers using a Buchner funnel connected to a vacuum system. Then, each of the filter papers were transferred to one weighed and dried aluminum-weighing dish.

Combinations of dishes, sludge samples, and filter papers were heated in the oven at 105°C for 1 h. After cooling in a desiccator, they were weighed again. Thus, the TSS values were determined by Equation (2.10).

$$TSS = \frac{(W_1 - W_2 - W_3)}{V} \quad (2.10)$$

where,

W_1 = sum of the weights of the dried filter paper, dish and solids of the sample (mg);

W_2 = weight of the dried filter paper (mg);

W_3 = weight of the dried dish (mg); and

V = volume of the sample (L).

To determine the VSS concentrations, the combinations of dishes, sludge samples, and filter papers after drying in the oven were burned in a furnace (Thermo Scientific Lindberg® Blue M® Muffle Furnace) at 550°C for 15 min. After cooling in a desiccator, they were also weighed. Thus, the VSS values were determined by Equation (2.11), where W_4 is the sum of the weights of the solids of the sample and the dish after burning.

$$VSS = \frac{(W_1 - W_2 - W_3) - (W_4 - W_3)}{V} = TSS - \frac{(W_4 - W_3)}{V} \quad (2.11)$$

2.8.4. Total organic carbon (TOC) and total nitrogen (TN)

A Teledyne Tekmar Apollo 9000 Combustion TOC/TN Analyzer equipped with an automated sampler measured TOC and TN concentrations. Before sample analyses, the TOC/TN analyzer was calibrated and samples were centrifuged at 5,000 rpm for 10 min (Thermo Scientific Heraeus Multifuge X1). Standards were prepared by adding a carbon source or a nitrogen source to distilled water to achieve determined levels of carbon or nitrogen. The reagent solutions were prepared as follows:

- 1) Potassium hydrogen phthalate (KHP) was used as an organic carbon source for TOC calibration. The KHP was dried in an oven at 105°C for 2 h prior to the preparation of stock standard solution and stored in a desiccator. For preparation of a 1,000 mg/L of KHP stock standard solution, an accurate 2,125 mg of KHP was dissolved in distilled water and diluted to 1 L. A series of standard solutions, covering the expected range of sample concentrations, such as 1–400 mg/L,

was prepared by accurately diluting the 1,000 mg/L of stock standard solution with distilled water. Through running TOC standard calibration analysis, a TOC calibration curve for the range 1–400 mg/L was obtained for analyzing TOC concentrations.

- 2) Potassium nitrate (KNO₃) was used as a nitrogen source for TN calibration. The KNO₃ was dried in the oven at 80°C and cooled in the desiccator; then, 7.22 g of it was dissolved in distilled water and diluted to 1 L in order to prepare 1,000 mg/L of stock standard solution. A series of working standard solutions covering the expected range of sample concentrations, such as 1–20 mg/L, were prepared by accurately diluting the 1,000 mg/L of stock standard solution with distilled water. Through running TN standard calibration analysis, a TN calibration curve for the range 1–20 mg/L was obtained for analyzing TN concentrations.

Thus, TOC and TN removal efficiencies were determined by Equations (2.12) and (2.13), respectively. Using the influent (in) and effluent (eff) values for each parameter.

$$TOC = \frac{(TOC_{in} - TOC_{eff})}{TOC_{in}} \times 100\% \quad (2.12)$$

$$TN = \frac{(TN_{in} - TN_{eff})}{TN_{in}} \times 100\% \quad (2.13)$$

2.8.5. Biochemical oxygen demand (BOD)

Respirometry assays were used to measure the oxygen uptake of the microorganisms in the SWW media. Respirometry experiments were performed using a BI-2000 electrolytic respirometer (Bioscience BI-2000 Electrolytic, Allentown, PA) in order to observe the biodegradability of the untreated and treated wastewater samples while measuring their BOD₅. The respirometer has eight 1 L bioreactor vessels, which were prepared according to the *standard methods* (APHA, 1998, 2012). Each respirometer bioreactor was loaded with 10 mL of acclimatized activated sludge, 10 mL of the wastewater sample, and filled up to 1 L with distilled water. The bioreactors required continuous aeration to obtain air saturation conditions and continuous agitation, which were provided automatically by the equipment. Respirometer tests were carried out for 120 h (5-days) or more if ultimate BOD (BOD_U) was needed. The temperature in each reactor vessel was constant at 25°C with an oxygen generation rate of 75 mg/L. Cumulative oxygen uptake data was recorded every 0.05 h. The data was accessed on computer screen through the instrument software. Two control samples, untreated solution and sludge, were used as control.

2.8.6. Total phosphorous (TP)

The analysis of the TP was carried out according to Section 4500P of Standard Methods (APHA, 1999). Since phosphorus exists in several distinct forms in wastewater samples and the approved test method measures only the orthophosphate form, a pre-treatment method was used to convert the various forms of phosphate-phosphorus to the orthophosphate form.

The samples were digested to convert both the polyphosphate and the organic phosphate to the orthophosphate form at the same time. After digestion, the vanadomolybdophosphoric acid colorimetric method (Orbeco-Hellige MC500 Multi-Parameter Colorimeter, Sarasota, FL) was used for routine analysis in the range of 1 to 20 mgTP/L.

2.8.7. Chemical oxygen demand (COD)

COD analysis was performed using pre-packaged mercury-free and premixed COD vials based on Section 5220 of *Standard Methods* (APHA, 1998, 2012). Three types of COD vials with the ranges 5-150, 20-900 and 100-4,500 mgCOD/L were used accordingly. A COD reactor was preheated to 150°C before testing.

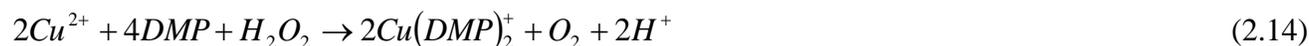
During every test, a 2.5 mL sample was carefully added into one COD vial of ranges 5-150 or 20-900 mgCOD/L, and 0.5 mL sample were carefully added into one COD vial of range 100-4,500 mgCOD/L. Then, the vial was thoroughly shaken by hand. COD standards and a DW blank were processed exactly the same as the samples. COD vials containing sample, COD standard, and blank, were heated in the COD reactor for 2 h at $150\pm 2^\circ\text{C}$, and then they were removed from the reactor and placed in a rack until they cooled and any suspended precipitate in the vials settled down.

After the outsides of vials were wiped to remove dust, the vials were placed into the Orbeco-Hellige MC500 Multi-Parameter Colorimeter one by one, to measure their COD concentrations under a standard curve covering the expected range of sample concentrations. The wavelength of 440, 600, and 600 nm were set for the ranges 5-150, 20-900 and 100-4,500 mgCOD/L, respectively. According to the requirements of the test method for using the COD vials, blanks of the ranges 20-900 and 100-4,500 mgCOD/L were used to set the zero in the colorimeter before sample testing.

2.8.8. Hydrogen peroxide (H₂O₂) residual

The H₂O₂ residual was measured with a UV-Visible Spectrophotometer (Ultrospec 1100 pro – Amersham Biosciences, Amersham, UK) at 454 nm using the copper (II) ion and 2,9-dimethyl-1,10-phenanthroline (neocuproine) method, also known as the copper-DMP method (Baga et al., 1988; Kosaka et al., 1998; Brandhuber and Korshin, 2009; Hamad et al., 2014; Bustillo-Lecompte et al., 2016a).

This method facilitates the determination of hydrogen peroxide in aqueous solutions based on reduction of copper (II) ions by H₂O₂ in the presence of excess of DMP to form a yellow copper (I)–DMP cationic complex, which is determined directly by spectrophotometric measurement at 454 nm. The stoichiometry follows the reduction of copper (II) with H₂O₂ as follows:



The Cu(DMP)₂⁺ product color is stable and not sensitive to light (Baga et al., 1988; Kosaka et al., 1998; Brandhuber and Korshin, 2009). The reagents and materials required by this method are readily available, including DMP (purchased and used as received from Sigma-Aldrich, Oakville, ON), Ethanol (purchased and used as received from BDH, Mississauga, ON), copper (II) sulfate pentahydrate (purchased from Sigma-Aldrich, Oakville, ON and dissolved in distilled water to make a 0.01 M copper (II) sulfate solution), a H₂O₂ solution (30% w/w) purchased and used as received from Sigma-Aldrich, Oakville, ON, and a phosphate buffer solution (0.1 M) prepared from K₂HPO₄ and NaH₂PO₄ (Sigma-Aldrich Oakville, ON) with pH adjusted to 7.0 by H₂SO₄ (1 N) and NaOH (50% w/w), accordingly.

All experiments involving the measurement of H₂O₂ were conducted in 10-mL volumetric flasks. 1 mL of each reagent, DMP, ethanol, and the 0.01 M copper (II) sulfate solution was added to the flask and mixed. A measured volume of H₂O₂ was added to the volumetric flask for a known concentration, and then the flask was filled up with distilled water to the 10-mL mark. The blank solution was prepared in the same manner but without H₂O₂.

After mixing, the absorbance of the sample was measured using UV-Visible Spectrophotometry at 454 nm. Using the difference in absorbance between the sample and blank solutions, a calibration curve was generated and the H₂O₂ concentrations were calculated, accordingly (Kosaka et al., 1998; Hamad et al., 2014; Bustillo-Lecompte et al., 2016a).

2.8.9. Light intensity and irradiance in the photoreactor

The light intensity is the output energy of the UV source and the irradiance is the amount of UV light arriving at the surface to be treated. Thus, the irradiance of the UV-C lamp of the photoreactor was determined by direct measurement using a digital radiometer (Spectroline DRC-100X, Spectronics Corp., Westbury, NY).

The radiometer consists of a sensitive electronic ammeter with a UV-C sensor probe (Spectroline DIX-254A, Spectronics Corp., Westbury, NY) that produces a current proportional to the incident irradiance. The radiometer takes direct measurements in the range of 0-19,990 $\mu\text{W}/\text{cm}^2$, precalibrated by Spectronics Corp. using fully characterized primary standard detectors. For each experimental trial in the UV/H₂O₂ photoreactor, the UV lamp was switched on for 30 min prior to the start of each experiment to guarantee light intensity stabilization within the photoreactor and to remove any possible background materials.

2.8.10. Biogas production and methane yield.

Biogas analysis was performed using a portable gas analyzer (Landtec Biogas 5000, Colton, CA) for CH₄, CO₂, O₂, and N₂-balance in a volume percentage measurement. The online portable biogas analyser was used for continuous accurate gas monitoring. This instrument also measured flow rate and temperature in the ABR. All experiments were repeated in triplicates; thus, average values were reported.

2.9. Quality control

In wastewater research, due to the importance of laboratory analyses, quality assurance programs to insure the reliability of the wastewater data are essential. Quality assurance programs have two primary functions in the laboratory. First, the programs should continually monitor the reliability, accuracy and precision of the results. The second function is the control of quality, to meet the program requirements for reliability. The steps in quality control (QC) vary with the type of analysis. In any instrumental method, calibration and revision of instrumental response are QC functions.

All of the experimental variables that affect the results should be considered, evaluated, and controlled. Thus, physical and chemical measurement methods on wastewater were performed by the following criteria:

- 1) The selected methods measured desired constituents of water samples in the presence of normal interferences with sufficient precision and accuracy to meet the water data needs.
- 2) The selected procedures used equipment and skills ordinarily available in the average laboratory for water pollution control or any water supply laboratory.
- 3) The selected methods were sufficiently tested to have established their validity.
- 4) The selected methods were sufficiently rapid to permit repetitive routine use in the examination of large numbers of water samples.
- 5) Statistical analysis and experimental design guaranteed reliability of the experimental data and further analysis of the information.

CHAPTER 3

SLAUGHTERHOUSE WASTEWATER CHARACTERISTICS, TREATMENT, AND MANAGEMENT IN THE MEAT PROCESSING INDUSTRY: A REVIEW ON TRENDS AND ADVANCES*

Abstract

A thorough review of advancement in slaughterhouse wastewater (SWW) characteristics, treatment, and management in the meat processing industry is presented. This study also provides a general review of the environmental impacts, health effects, and regulatory frameworks relevant to the SWW management. A significant progress in high-rate anaerobic treatment, nutrient removal, advanced oxidation processes (AOPs), and the combination of biological treatment and AOPs for SWW treatment is highlighted. The treatment processes are described and few examples of their applications are given. Conversely, few advances are accounted in terms of waste minimization and water use reduction, reuse, and recycle in slaughterhouses, which may offer new alternatives for cost-effective waste management. An overview of the most frequently applied technologies and combined processes for organic and nutrient removal during the last decade is also summarized. Several types of individual and combined processes have been used for the SWW treatment. Nevertheless, the selection of a particular technology depends on the characteristics of the wastewater, the available technology, and the compliance with regulations. This review facilitates a better understanding of current difficulties that can be found during production and management of the SWW, including treatment and characteristics of the final effluent.

Keywords: Slaughterhouse wastewater (SWW), wastewater treatment, combined processes, biological treatment, advanced oxidation processes (AOPs).

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3.1. Introduction

The increasing growth of world population has augmented the pollution of freshwater due to the inadequate discharge of wastewater, especially in developing countries (US EPA, 2004; Leitão et al., 2006; Gopala Krishna et al., 2009; Feng et al., 2009). For this reason, water and wastewater treatment has become crucial for the continuing development of the society. Moreover, the progressively stricter standards for effluent discharge worldwide have made the developing of advanced wastewater treatment technologies necessary (Environment Canada, 2000, 2012; US EPA, 2004; World Bank Group, 2007). Besides, the continuing decreasing availability of freshwater resources has rearranged the objectives in the wastewater treatment field from disposal to reuse and recycling. As a result, a high level of treatment efficiency has to be achieved. Given the differences in location, economic resources, living standards of different countries, and characteristics of water and its pollutants, many nations adopt diverse techniques for water and wastewater treatment (Daigger, 2009).

The meat-processing sector produces large volumes of slaughterhouse wastewater (SWW) due to the slaughtering of animals and cleaning of the slaughterhouse facilities and meat processing plants (MPPs). The meat processing industry uses 24% of the total freshwater consumed by the food and beverage industry (Table 3.1) and up to 29% of that consumed by the agricultural sector worldwide (Mekonnen and Hoekstra, 2012; Gerbens-Leenes et al., 2013).

Table 3.1. Freshwater consumption in beverage and food industries.

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Food Industry	Water consumption (%)
Meat Processing	24
Beverages	13
Dairy	12
Other Food	11
Fruits and Vegetables	10
Bakery and Tortilla Products	9
Grain and Oilseeds	9
Sugar and Confectionary	5
Animal Food	5
Seafood	2

SWW composition varies significantly depending on the diverse industrial processes and specific water demand (Matsumura and Mierzwa, 2008; Debik and Coskun, 2009; Bustillo-Lecompte et al., 2013, 2014). Slaughterhouses are part of a large industry, which is common to numerous countries worldwide where meat is an important part of their diet. Therefore, SWWs require significant treatment for a safe and sustainable release to the environment (Johns, 1995).

Nevertheless, review articles on SWW and the meat processing industry are not widely available (Bull et al., 1982; Tritt and Schuchardt, 1992; Johns, 1995; Salminen and Rintala, 2002; Mittal, 2006; Arvanitoyannis and Ladas, 2008), rather characterization of microorganisms present in SWW and disinfection are the focus in recent years (Franke-Whittle and Insam, 2013).

According to Mittal (2006), slaughterhouses and MPPs in Ontario, Canada, commonly discharge the SWW into the municipal sewer system after preliminary onsite treatment (Mittal, 2006). Thus, MMPs usually pay fines to dispose of their wastewater at municipal wastewater treatment plants (Massé and Masse, 2000a). According to Wu and Mittal (2011), there are approximately 142 MPPs in Ontario that can process 100-200 animals per month. About 53% of Ontario's slaughterhouses do not treat their wastewater prior to disposal. Only 16% of Ontario's slaughterhouses use dissolved air flotation (DAF) or aeration. The remaining 31% of slaughterhouses utilize passive systems such as storage tank or lagoon to settle solids.

This review aims to identify the most recent trends and advances in meat processing effluent management and SWW treatment technologies, common practices on storage, management, treatment, and disposal, along with SWW characteristics, guidelines, and regulations. Furthermore, this study presents current technologies based on the technical advances in efficiency, design, performance, and optimization of the SWW treatment processes for organics and nutrient removal, including biological treatment, combined processes, advanced oxidation processes (AOPs), and water reuse. Thus, the assessment of possible alternatives to minimize operational and maintenance (O&M) costs is also discussed.

3.2. Characterization of slaughterhouse wastewater

The global meat production was doubled in the last three decades (Mekonnen and Hoekstra, 2012; FAO, 2013). Bouwman et al. (2013) have projected a steady doubling growth of meat production until 2050. Furthermore, the production of beef has been increasing continuously in recent years, mostly in India and China due to income increases and the shift toward a western-like diet rich in proteins (Pingali, 2007). From 2002 to 2007, the annual global production of beef was increased to 14.7×10^6 metric tons, representing an increase of 29% over eight years (FAO, 2013). As a result, it can be inferred that the number of slaughterhouse facilities will increase, resulting in a greater volume of high-strength wastewater to be treated.

According to Table 3.1, the meat processing industry is one of the major consumers of freshwater in the food and beverage processing facilities, which makes slaughterhouses a significant producer of wastewater effluents (De Sena et al., 2009). The World Bank Group (2007) classifies a slaughterhouse plant as a meat processing facility that may consume between 2.5 and 40 m³ of water per metric tons of meat produced. Common SWW characteristics have been described in previous studies and summarized in Table 3.2.

Table 3.2. General characteristics of slaughterhouse wastewater.

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Parameter	Range	Mean
TOC (mg/L)	70–1,200	546
BOD ₅ (mg/L)	150–4,635	1,209
COD (mg/L)	500–15,900	4,221
TN (mg/L)	50–841	427
TSS (mg/L)	270–6,400	1,164
pH	4.90–8.10	6.95
TP (mg/L)	25-200	50
Orto-PO ₄ (mg/L)	20–100	25
Orto-P ₂ O ₅ (mg/L)	10–80	20
K (mg/L)	0.01-100	90
Color (mg/L Pt scale)	175-400	290
Turbidity (FAU ^a)	200-300	275

^a FAU, formazin attenuation units.

SWW is usually evaluated in terms of bulk parameters due to the specific amounts of SWW and pollutant loads related to the animals slaughtered and processed that vary among the meat processing industry, usually containing considerable amounts of total phosphorus (TP), total nitrogen (TN), total organic carbon (TOC), chemical oxygen demand (COD), total suspended solids (TSS), and biochemical oxygen demand (BOD) (Tritt and Schuchardt, 1992; Johns, 1995; Mittal, 2006; Cao and Mehrvar, 2011; Wu and Mittal, 2011; Barrera et al., 2012; Bustillo-Lecompte et al., 2013, 2014).

SWW is considered detrimental worldwide due to its complex composition of fats, proteins, and fibers from the slaughtering process (Johns, 1995; Ruiz et al., 1997; Wu and Mittal, 2011; Bustillo-Lecompte et al., 2014). The major part of the contamination is caused by blood and by stomach and intestinal mucus (Tritt and Schuchardt, 1992). Furthermore, SWW contains high levels of organics, pathogenic and non-pathogenic microorganisms, and detergents and disinfectants used for cleaning activities (Massé and Masse, 2000a; Debik and Coskun, 2009). SWW samples also include nutrients, heavy metals, color, and turbidity, among others. It is also important to note that disinfectant, cleaning agents, and pharmaceuticals for veterinary purposes can be present in the SWW (Tritt and Schuchardt, 1992).

In the present study, a questionnaire was distributed to 128 slaughterhouses licensed by the Ontario Ministry of Agriculture and Rural Affairs (OMAFRA, 2014) in order to gather information on the current characteristics of the actual SWW, type of animals processed, and the type of treatment, storage, or disposal methods used in Ontario, Canada. Thirty-nine questionnaires were returned for an overall response rate of 30.47%. It was found that 51% of the MPPs do not treat their wastewater onsite; 17% use aerobic treatment, i.e. DAF; 32% utilize passive systems such as storage tanks to settle solids; and only 2% utilize grease trap for fat separation and blood collection.

Moreover, a typical MPP in Ontario has been established more than 20 years ago, it operates 30 weeks per year, slaughters approximately 600 animals per day, with a maximum capacity of over 2500 animals/day, and mean water usage per day of 2000 m³. Besides, there were 10 SWW samples taken from selected provincially licensed MPPs at the time of study. Table 3.3 shows overall SWW characteristics gathered from the returned questionnaires and the 10 SWW samples.

Table 3.3. Characteristics of slaughterhouse wastewater from selected provincially inspected meat processing plants in Ontario.

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Parameter	Range	Mean
TSS (mg/L)	0.39–9,938	3,092
COD (mg/L)	527–14,256	5,577
BOD (mg/L)	200–8,231	2,649
TOC (mg/L)	72.5–1,718	862
TN (mg/L)	60–339	156
TP (mg/L)	25.7–75.9	42.8
Orto-PO ₄ (mg/L)	30.1–77.3	52.1
Orto-P ₂ O ₅ (mg/L)	27.2–76.2	48.3
K (mg/L)	0.01–0.06	0.04
Pb (mg/L)	n/a	34.3
Color (mg/L Pt scale)	178–391	289
Turbidity (FAU ^a)	271–279	275
pH	6.0–6.9	6.5

^a FAU, formazin attenuation units.

3.3. Slaughterhouse wastewater guidelines and regulations

Regulations and guidelines are essential components in dealing with the environmental impact of slaughterhouses in the meat processing industry. The treatment systems used in the meat processing industry are commonly viewed as a regulatory requirement. Therefore, it increases capital and O&M costs, which yields negative financial impacts (Sneeringer, 2009). Nevertheless, compliance with current environmental legislation may provide an extra source of revenue by including energy recovery from the treatment, such as biogas production from anaerobic treatment. The standards and regulations governing the meat processing industry vary significantly worldwide. In several countries, slaughterhouses are regulated by tradition and practice (Casani et al., 2005).

SWWs have been considered as an industrial waste in the category of agricultural and food industries and classified as one of the most harmful wastewaters to the environment by the United States Environmental Protection Agency (US EPA). SWW discharge may cause deoxygenation of rivers and

contamination of groundwater (US EPA, 2004). Typically, anaerobic treatment is used because of the high organic concentrations present in SWWs (Cao and Mehrvar, 2011; Akbaripour et al., 2014). Nevertheless, a complete degradation of organic matter present in SWW is not conceivable using anaerobic treatment alone. MPP effluents contain solubilized organic material that is adequate for posttreatment using aerobic systems. For that reason, either anaerobic or aerobic processes should not be used as the sole treatment alternative because of the characteristics of their final effluents that are required to comply with current effluent discharge limits and standards (Chan et al., 2009; Bustillo-Lecompte et al., 2013).

Table 3.4 describes the standard levels and concentration limits of organic constituents to be discharged into water bodies as recommended by different worldwide agencies, including the Australian and New Zealand Environment and Conservation Council (ANZECC, 2000), Environment Canada (2000, 2012), the Council of the European Communities (CEC, 1991), US EPA (2004), among others.

Table 3.4. Comparison of standard limits of different jurisdictions worldwide for slaughterhouse wastewater discharge.

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Parameter	World Bank Standards	EU Standards	US Standards	Canadian Standards^a	Australian Standards
BOD (mg/L)	30	25	26	5–30	6-10
COD (mg/L)	125	125	n/a	n/a	3 × BOD
TSS (mg/L)	50	35	30	5–30	10-15
TN (mg/L)	10	10	8	1	0.1-15

^a In the case of the Canadian standards the range is specific to freshwater lakes and slow-flowing streams: 5 mg/L; rivers, streams, and estuaries: 20 mg/L; and shoreline: 30 mg/L.

However, the selection of a particular treatment technology is subject to the SWW characteristics, available technology, and compliance with current regulations. For instance, some MPPs are allowed to discharge their effluent into the municipal sewer system after demonstrating an adequate reduction of BOD loads by preliminary treatment (Mittal, 2006). The main factors determining whether a plant can discharge into a municipal sewer or not are related to the plant size as well as the volume and organic concentration of the wastewater produced (US EPA, 2004). Benefits of the combined anaerobic-aerobic processes include potential resource recovery from the conversion of organic pollutants into biogas with

high overall treatment efficiency (Chan et al., 2009). However, SWWs may contain toxic and non-biodegradable organic substances that make biological treatment alone insufficient (Oller et al., 2011). Thus, advanced oxidation processes (AOPs) can be employed as an alternative to improve the SWW biodegradability containing recalcitrant, non-biodegradable, refractory, and toxic compounds.

3.4. Slaughterhouse wastewater treatment

Direct discharge of raw SWW effluents to a water body is impractical due to their high organic strength. Therefore, appropriated disposal, preliminary treatment, and/or further treatment of SWW are performed. The first step in SWW management is the minimization of the process inputs (Johns, 1995). It is usually preferable to identify and minimize wastewater generation at its source. Although typical water consumption varies considerably in the meat processing business, a regular slaughterhouse generates vast amounts of wastewater and is commonly not an efficient user of fresh water. Recovery of valuable by-products from SWW is currently focused on high-quality effluents, biogas, fertilizers, and nutrients (Amorim et al., 2007; Kist et al., 2009).

SWW treatment methods are similar to current technologies used in municipal wastewater and may include preliminary, primary, secondary, and even tertiary treatment. Thus, SWW management methods after preliminary treatment are various, but they can be divided into five major subgroups: land application, physicochemical treatment, biological treatment, AOPs, and combined processes (Valta et al., 2015). Each system has its own advantages and disadvantages, which are discussed below.

Land application usually involves direct irrigation of the SWW onto agricultural land (Bull et al., 1982; Mittal, 2006). Physicochemical treatment involves the separation of the SWW into various components, typically the separation of solids from the liquor by sedimentation or coagulation/flocculation, and removal of pollutants using electrocoagulation (EC) and membrane technologies (Bull et al., 1982; Johns, 1995; San José, 2004; Mittal, 2006; Eryuruk et al., 2014; Almandoz et al., 2015). Biological treatment is divided into anaerobic and aerobic systems as well as constructed wetlands (CWs). Aerobic systems are more common since they commonly operate at a higher rate than anaerobic systems; whereas, anaerobic systems require less complex equipment since no aeration system is required; nevertheless, both anaerobic and aerobic systems may be further sub-divided into other processes, which have their own advantages and disadvantages (Bull et al., 1982; Tritt and Schuchardt, 1992; Johns, 1995; San José, 2004; Mittal, 2006; Bugallo et al., 2014; Vymazal, 2014). AOPs are diverse

and include UV/H₂O₂ and UV/O₃ for the oxidation and degradation of organic and inorganic materials present in SWW through reactions with hydroxyl radicals ($\cdot\text{OH}$) (Mittal, 2006; Melo et al., 2008; Luiz et al., 2009, 2011; Cao and Mehrvar, 2011; Barrera et al., 2012; Bustillo-Lecompte et al., 2013, 2014). Finally, combined processes are cost-effective with high removal efficiencies that can lead to a reduction in O&M costs compared to individual processes (Tritt and Schuchardt, 1992; Chan et al., 2009; Luiz et al., 2011; Cao and Mehrvar, 2011; Bustillo-Lecompte et al., 2013, 2014).

3.4.1. Preliminary treatment

In preliminary treatment, all solids and large particles generated during the slaughtering process are separated from wastewater. Typical unit operations for the preliminary removal of TSS in wastewater include regular screeners, strainers, or sieves. Large solids in wastewater with a diameter of 10–30 mm are retained on the mesh of the screener. Rotary screeners are used to retain solids with a diameter of more than 0.5 mm in order to avoid fouling, clogging, or jamming of the equipment. Screw screen compactors are used to transport, dewater, and compact all the remaining solids from the previous screeners, minimizing the moisture content and volume in order to be treated as solid waste (San José, 2004; Mittal, 2006). Other pre-treatments include catch basins, homogenization/equalization, flotation, and settlers. Furthermore, screening can separate up to 60% of the solids from the SWW and remove more than 30% of the BOD (Mittal, 2006).

3.4.2. Land application

In land application, biodegradable materials can be used to provide nutrients to the soil by directly placing them into the land. One drawback of the land application is related to the temperature and the geography (San José, 2004). For instance, the land application in temperate countries is not feasible throughout the year due to the winter season. Therefore, the SWW requires being stored during that period; thus, energy usage related to the treatment and transportation increases. Other disadvantages include aesthetics, odor, soil contamination, possible surface and groundwater pollution, and pathogens presence and persistence (Avery et al., 2005). On the other hand, advantages of land application include the recovery of useful by-products from the SWW, alternative source of fertilizer, and improvement of soil structure (Mittal, 2004, 2006).

3.4.3. Physicochemical treatment methods

Following preliminary treatment, it is recommended to send the effluent to a subsequent primary or secondary treatment, depending on the strength of the SWW. One of the typical methods of the primary treatment is the DAF process, especially for reducing fat, TSS, and BOD in SWW (Al-Mutairi et al., 2008; De Nardi et al., 2011). Physicochemical treatment methods usually involve the separation of solids from the liquid. Different physicochemical treatment technologies are discussed in the following subsections.

3.4.3.1. Dissolved air flotation

DAF systems refer to the water-solid separation method by introducing air into a SWW influent, where the air is introduced from the bottom of the vessel. Hence, light solids, fat, and grease are transported to the surface forming a sludge blanket, where a scraping assembly constantly removes scum.

The efficiency of the DAF system can be enhanced by adding polymers and other flocculants for pH adjustment and flocculation of particulate matter. Blood coagulants such as ferric chloride and aluminum sulfate can be also added to the SWW to promote protein aggregation and precipitation in addition to fat and grease flotation. The DAF process efficiencies for COD and BOD removal are usually from 30 to 90% and from 70 to 80%, respectively. DAF systems are also capable of achieving moderate to high nutrient removal (Johns, 1995; Mittal, 2006; Al-Mutairi et al., 2008; De Nardi et al., 2011). Conversely, DAF drawbacks are related to regular malfunctioning and poor TSS separation (Kiepper, 2001).

3.4.3.2. Coagulation and flocculation

Coagulants and flocculants are added into a reactor vessel where the floc is conditioned. The ideal size for separation during flotation is searched, and it is necessary to balance the pH after addition of the coagulant in order to achieve an appropriate flocculation (San José, 2004). Aluminum sulfate, ferric chloride, ferric sulfate, and aluminum chlorohydrate have been used as coagulants to treat SWW. Results show TP, TN, and COD removals of up to 99.9, 88.8, and 75.0%, respectively, using polyaluminum chloride as the reagent. Moreover, if inorganic coagulant aids are used, the sludge volume can be reduced by 41.6% (Núñez et al., 1999; Aguilar et al., 2002; Mittal, 2006; De Sena et al., 2008).

Satyanarayan et al. (2005) studied the physicochemical treatment of SWW effluent using anionic polyelectrolyte, ferrous sulfate, lime, and alum as coagulants. Among these coagulants, lime alone achieves removal rates of up to 38.9, 36.1, and 41.9% for BOD, COD, and TSS, respectively. The combination of ferrous sulfate and lime improves the COD removal rate to 56.8%. Likewise, the combination of lime and alum also results in an increased COD removal of up to 42.6%. On the other hand, using combined ferrous sulfate and anionic polyelectrolyte, although not cost-effective, results in good removal rates of up to 54.2, 49.6, and 43.8% for TSS, BOD, and COD, respectively. Whereas, if alum is used in combination with lime, the generation of sludge is increased.

Amuda and Alade (2006) used the coagulation-flocculation technology at the laboratory-scale for the removal of TP, TSS, and COD from SWW. Several coagulants including ferric chloride, ferric sulfate, and alum were used. Results show that although alum was effective for the removal of TP and TSS from SWW, ferric sulfate was more efficient in reducing COD. Results show maximum COD, TP, and TSS removal efficiencies of up to 65, 34, and 98%, respectively. Tariq et al. (2012) used lime and alum individually and in combination as coagulants for the treatment of SWW. Results show that as the alum dose increases, COD removal increases to a maximum of 92% along with the sludge volume, which makes the process not feasible. Conversely, an increase in lime dosage increased the COD reduction to a maximum of 74%, whereas the sludge settling was high, and the sludge volume decreased as compared to that of alum. At the end, the combined dosages of lime and alum give a maximum removal of 85% in COD with low sludge volume.

3.4.3.3. *Electrocoagulation*

The EC process has been recently used for SWW treatment as a cost-effective advanced wastewater treatment technology. EC has been confirmed to be an effective technology for the removal of organics, nutrients, heavy metals, and even pathogens from SWW by introducing an electric current without adding chemicals (Koby et al., 2006; Emamjomeh and Sivakumar, 2009; Bayar et al., 2011; Qin et al., 2013). Figure 3.1 illustrates a typical EC reactor. Al, Fe, Pt, SnO₂, TiO₂, among others, can be utilized as electrodes for the EC process, being Fe and Al the most widely used. Thus, the EC process involves onsite generation of M³⁺ ions using sacrificial anodes. Additionally, these sacrificial electrodes might be interacting with H⁺ ions in an acidic medium, or with OH⁻ ions in an alkaline medium (Bayramoglu et al., 2006; Koby et al., 2006; Bayar et al., 2011, 2014; Ozyonar and Karagozoglu, 2014).

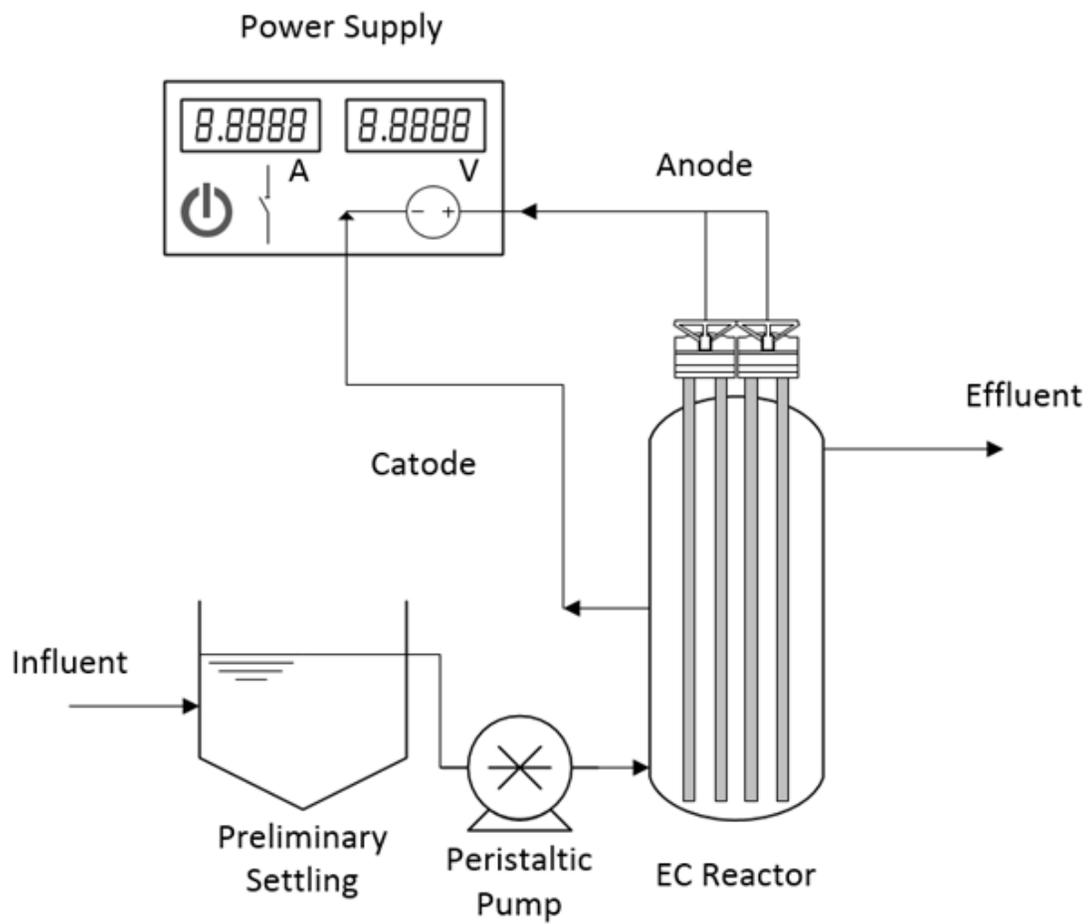


Figure 3.1. Schematic diagram of a typical electrocoagulation unit.

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Kobyas et al. (2006) studied the influence of pH, operating time, electrode material, and current density of the EC process for SWW treatment on oil-grease and COD removal, sacrificial electrode and electrical energy consumption. Up to 93% of COD was removed using Al as the electrode material, whereas maximum oil-grease efficiency was obtained using Fe as the electrode material, reaching 98% removal. Nevertheless, it was found that further work is required at the pilot-scale to assess the cost-effectiveness of the EC process.

Bayramoglu et al. (2006) conducted a cost-effectiveness analysis (CEA) for the treatment of SWW using EC with a particular focus on COD removal. Total operating cost included O&M, electricity, sacrificial electrodes (Fe and Al) depreciation, and sludge handling costs. Other performance parameters included pH, current density, and operating time. Results show that Fe sacrificial electrodes are more cost-effective than Al electrodes, with total operating costs between 0.30 and 0.40 \$/m³, nearly 50% of the total costs of using Al. Similar results were obtained by Ozyonar and Karagozoglu (2014), when calculating total costs for Al and Fe sacrificial electrodes at optimum conditions. Al electrodes were found less cost-effective than Fe electrodes with total costs of 2.76 and 0.87 \$/m³, respectively.

Likewise, Asselin et al. (2008) evaluated the EC process in economic terms for the removal of organic compounds from SWW. Experiments were conducted at laboratory pilot-scale by using mild steel and Al sacrificial electrodes. Results show that using mild steel bipolar electrodes achieves COD, BOD, TSS, turbidity, and oil-grease removals of up to 84, 87, 93, 94, and 99%, respectively. Thus, involving a total cost, including energy, electrode consumptions, chemicals, and sludge disposal, of 0.71 \$/m³ of treated SWW effluent, which is comparable to that found by Bayramoglu et al. (2006).

Awang et al. (2011) used the EC process for the post-treatment of SWW. The effects of current density, reaction time, and influent COD on color, COD, and BOD removal efficiencies were investigated using a 3-level factorial design and response surface methodology (RSM). The optimum conditions were obtained at COD influent concentrations of 220 mg/L, 55 min reaction time, and current density near 30 mA/cm². Thus, a removal response of 96.80, 81.30, and 85.00% was achieved for color, BOD, and COD, respectively.

On the other hand, Bayar et al. (2011, 2014) studied the influence of current density and pH on the treatment of SWW by means of EC with Al electrodes. High removal efficiencies at low pH and current density values were obtained. Thus, COD removal efficiencies of up to 85% were obtained with the

current density of 0.5 mA/cm² at pH of 3.0. Likewise, Ahmadian et al. (2012) examined the performance of EC for SWW treatment in a batch system using Fe electrodes. Augmenting current density, operating time and electrode number improved organic matter and nutrient removal rates. Results show removal efficiencies of up to 97, 93, 84, and 81% for BOD, COD, TN, and TSS, respectively.

3.4.3.4. Membrane technology

Membrane technology is becoming an alternative for SWW treatment. Reverse osmosis (RO), nanofiltration (NF), ultrafiltration (UF), and microfiltration (MF) processes are able to remove particles, colloids, and macromolecules depending on the pore size (Table 3.5). Membrane processes are also increasingly used for removal of bacteria, microorganisms, particulates, and organic matter in SWW treatment (Almandoz et al., 2015).

Table 3.5. Comparison of different membrane dimensions and pore size exclusion used in SWW treatment.

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Membrane type	Pore size (µm)	TOC removal (%)	COD removal (%)	BOD removal (%)	TN removal (%)	Reference
Microfiltration (MF)	0.08–0.55	44.81	90.63	-	45.22	Almandoz et al. (2015)
Ultrafiltration (UF)	0.03	75–96	83–97	-	27-44	Gürel and Büyükgüngör (2011)
Ultrafiltration (UF)	0.01–0.10	-	94.52–94.74	97.80–97.89	-	Yordanov (2010)
Reverse Osmosis (RO)	0.001–0.005	-	85.8	50	90	Bohdziewicz and Sroka (2005)

Bohdziewicz and Sroka (2005) studied the performance of the RO process for SWW treatment as secondary effluent. The raw SWW was first pretreated using activated sludge (AS). Thus, the characteristics of the influent SWW for RO treatment were 76.0, 10.0, 3.6, and 13.0 mg/L for COD, BOD, TP, and TN, respectively. Results showed a removal efficiency of 85.8, 50.0, 97.5, and 90.0%, after RO treatment, for COD, BOD, TP, and TN, respectively. Therefore, it can be concluded that RO is a feasible technology for SWW post-treatment.

Yordanov (2010) investigated the feasibility of using UF for SWW treatment. Results showed that the UF could be an efficient purification method by achieving 98 and 99% removal of TSS and fats, respectively. The efficiencies of BOD and COD removals were 97.80-97.89 and 94.52-94.74%, respectively.

Gürel and Büyükgüngör (2011) investigated the performance of membrane bioreactors (MBRs) for nutrients and organics removal from SWW. The initial COD, TP, and TN concentrations were 571, 16, and 102 mg/L, respectively. An UF membrane was utilized in the MBR. Up to 44, 65, 96, and 97% removals were obtained for TN, TP, TOC, and COD, respectively. Although organic matter was successfully removed, a high nitrate concentration in the treated effluent remained. Thus, denitrification is required to further treat this effluent.

Almandoz et al. (2015) evaluated the effectiveness of a MF ceramic composite membrane (CM). The results show a total insoluble residue rejection of 100%, high bacterial removal (87-99%), as well as TOC, TN, and COD removal rates of 44.81, 45.22, and 90.63%, respectively. Thus, making the ceramic CM suitable for MF treatment of SWW.

Although membrane processes can achieve high organic removal, nutrients' removals require this process to be coupled with another conventional process (Gürel and Büyükgüngör, 2011). Furthermore, membrane processes can face major problems of fouling while processing highly concentrated feed streams such as SWW, which is difficult to remove and can greatly restrict the permeation rate through the membranes due to the formation of thick biofouling layers onto the membrane surfaces (He et al., 2005; Selmane et al., 2008).

3.4.4. Biological treatment

Reducing BOD concentration in SWW is the focus of the secondary treatment by removing soluble organic compounds that remain after primary treatment (Pierson and Pavlostathis, 2000). Biological treatment is usually applied as a secondary treatment process in MPPs, where aerobic and anaerobic digestion are used as individual or combined processes depending on the characteristics of the SWW being treated (Martínez et al., 1995).

Biological treatment is used to remove organics and eventually pathogens from SWW effluents using microorganisms. Furthermore, the biological treatment is able to remove up to 90% BOD from MPP effluents by aerobic or anaerobic processes (Mittal, 2006). Biological treatment may include different combinations of various processes including anaerobic, aerobic, and facultative lagoons, AS, and trickling filters among others (Massé and Masse, 2000a).

3.4.4.1. Anaerobic treatment

Anaerobic digestion is the preferred biological treatment that is applied in SWW treatment due to its effectiveness in treating high-strength wastewater (Cao and Mehrvar, 2011). During anaerobic treatment, different bacteria degrade organic compounds into CO₂ and CH₄ in the absence of oxygen. Besides, anaerobic systems have several advantages such as high COD removal, low sludge production (5-20%) compared to those of aerobic systems, and less energy requirements with potential nutrient and biogas recovery (Massé and Masse, 2000a; Mittal, 2006; Chan et al., 2009; Bustillo-Lecompte et al., 2014).

Although anaerobic treatment possesses great advantages, it hardly produces effluents that comply with current discharge limits and standards (Table 3.4). Although anaerobic treatment is an efficient process, the SWW organic strength makes it difficult to achieve complete stabilization of the organic compounds (Chan et al., 2009). Hence, anaerobically treated effluents usually need additional post-treatment, in which the removal of organic matter and other constituents such as TN, TP, and pathogenic organisms, is completed (Chernicharo, 2006; Oliveira and Von Sperling, 2009; Gomec, 2010). Moreover, the associated higher space-time yield contributes considerably to the economic viability of anaerobic treatment plants (Tritt and Schuchardt, 1992). Thus, the combination of anaerobic-aerobic systems is a potential alternative to conventional methods in order to satisfy current effluent discharge standards (Chan et al., 2009; Bustillo-Lecompte et al., 2013). Typical configurations for SWW anaerobic treatment include anaerobic baffled reactor (ABR), anaerobic filter (AF), anaerobic lagoon (AL), up-flow anaerobic sludge blanket (UASB), and anaerobic sequencing batch reactor (SBR).

3.4.4.1.1. Anaerobic baffled reactor

ABRs are considered an optimized version of a common septic tank. ABRs have a series of compartments and baffles under which the SWW flows under and over from the inlet to the outlet. Since there is an increased contact time with the active biomass, a higher biodegradation occurs. The up-flow

compartments provide an improved removal of organics with BOD and COD removals of up to 90% (Barber and Stuckey, 1999; Kuşçu and Sponza, 2005).

Cao and Mehrvar (2011) evaluated the performance of the combined ABR and UV/H₂O₂ processes at a laboratory-scale to treat SWW. Results show that combined processes had higher removal efficiencies for SWW treatment rather than using individual processes. Maximum TOC removals of up to 95% were obtained for influent concentrations of 973 mgTOC/L after 3.8 days of treatment.

Bustillo-Lecompte et al. (2013) studied individual biological treatment using an ABR at a laboratory-scale to treat SWW with an influent concentration of 183.35 mgTOC/L and 63.38 mgTN/L. Maximum removals of up to 88.88 and 51.52% were achieved for TOC and TN, respectively.

Bustillo-Lecompte et al. (2014) also evaluated the effectiveness and performance of the ABR process for the treatment of SWW using a CEA by assessing the total electricity cost, hydraulic retention time (HRT), and removal percentage of TOC. Results show that costs increase with the amount of TOC removed, especially if high TOC removal rates are required.

As a result, if low or intermediate amounts of TOC are to be removed, the ABR as an individual process can be comparable to combined processes in economic terms since electricity costs gradually increase. Therefore, biogas production is an important asset to be used due to its potential energy recovery that will be translated into cost savings for MPPs because of the characteristics of SWWs (Bustillo-Lecompte et al., 2014).

3.4.4.1.2. Anaerobic filter

Anaerobic filters (AFs) are fixed-bed biological reactors with filtration chambers. AFs are commonly found working in series. When the SWW runs through the filtration chambers, particles are confined inside; then, the organic material is removed by the active biomass attached to the filter surface. AFs are used as secondary treatment due to its high solid removal and biogas recovery rates. An AF is designed as an anaerobic digestion column packed with different types of media (Mittal, 2006). A typical anaerobic filter is presented in Figure 3.2.

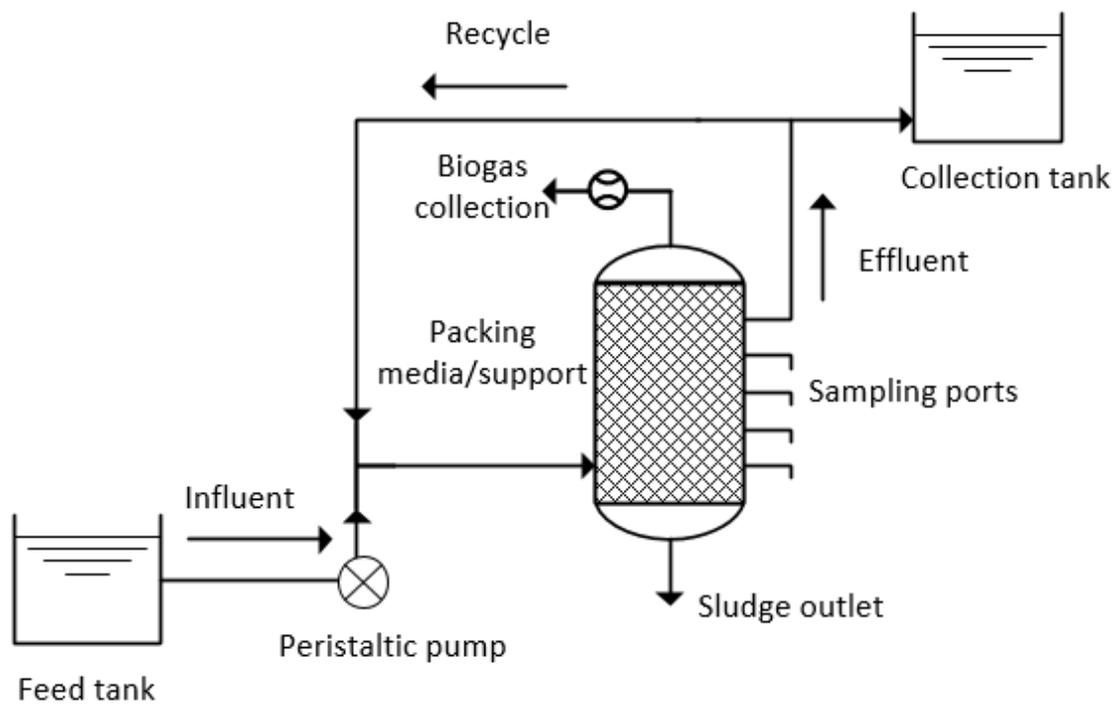


Figure 3.2. Schematic diagram of a typical anaerobic filter system.

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The performance of up-flow anaerobic filters (UAFs) has been examined under thermophilic and mesophilic conditions for SWW treatment (Gannoun et al., 2009, 2013). The results showed that COD removal efficiencies of up to 90% could be achieved for organic loading rates (OLRs) of 9000 mg/L day under mesophilic conditions and 72% under thermophilic conditions.

Rajakumar et al. (2011) evaluated the performance of an UAF reactor for SWW treatment under low up-flow velocity, at mesophilic conditions of up to 35°C. COD removals of 79% were achieved at OLRs of 10.05 kg/m³ day and HRT of 12 h. The average produced methane varied between 46 and 56%. The lower velocity used in the study conducted by Rajakumar et al. (2011) allowed an active microbial formation with stable pH demonstrating that SWW can be treated using AFs under low up-flow velocity.

Stets et al. (2014) assessed the performance of AF bioreactors for SWW treatment by evaluating the influence of the characteristics of the support medium, substrate, and microorganisms present in the sludge. Three AF configurations were studied using different support media resulting in maximum COD removals of up to 80% and TN removals of up to 90% at HRT of 1 day.

Martinez et al. (2014) compared the effectiveness of two up-flow anaerobic packed-bed filters (UAPFs) for SWW treatment at a laboratory-scale, under mesophilic conditions, and using different packing material. The production of CH₄ was assessed at various OLRs and feeding conditions. The COD removal reached 60% for an influent concentration of up to 15800 mg/L. The UAPF was proven self-sufficient in terms of energy requirements, providing sufficient heating power for the SWW treatment plant.

3.4.4.1.3. Anaerobic lagoon

ALs are popular in countries where weather and land availability permit the construction of lagoons for the treatment of SWW (Johns, 1995; Mittal, 2006). The wastewater influent usually flows from the bottom of the lagoon, and although some gas mixing may be present, ALs are not mechanically mixed. Thus, a scum layer is typical to appear on the surface of the ALs, ensuring anaerobic conditions and low heat loss. Typical ALs are constructed with a depth of 3–5 m for HRTs of 5–10 days. Efficiencies of ALs to remove BOD, COD, and TSS have been reported to be 97, 96, and 95%, respectively (US EPA, 2004; Mittal, 2006; McCabe et al., 2014).

The main drawbacks of ALs are related to odor regeneration and weather conditions. Therefore, synthetic floating covers are used to trap odor and collect biogas; these covers must be durable to resist inclement weather, temperature change, wind, ice and snow accumulation (Mittal, 2006). On the other hand, ALs are the preferred option because of their simplicity and low O&M costs (McCabe et al., 2014).

3.4.4.1.4. Up-flow anaerobic sludge blanket reactor and anaerobic sequencing batch reactor

An anaerobic SBR requires low capital and O&M costs. The feeding, reactions, settling, and decanting stages take place in the same basin and anaerobic SBRs also eliminate the requirements of complete mixing. Nevertheless, intermittent mixing may occur in the course of the reacting cycles (Massé and Masse, 2000a; Mittal, 2006). Moreover, in order to optimize the performance of anaerobic SBRs, an intermittent feeding strategy of the SWW influent eliminates the need for a recycling stream or an equalizing tank (Masse and Massé, 2005).

UASB reactors are similar to anaerobic SBRs. The UASB process uses granules to capture bacteria; the SWW enters from the bottom of the reactor, flows upward through the sludge blanket, the biomass film, and exits at the top of the vessel. Essentially, UASB reactors consist of three stages: liquid as SWW, solid as biomass, and gas as CO₂ and CH₄ produced during digestion (Mittal, 2006; Del Nery et al., 2007, 2008).

Caldera et al. (2005) evaluated the performance of a UASB reactor of 4 L at mesophilic conditions for the treatment of SWW. Influent COD concentrations were varied from 1820 to 12790 mg/L. Experiments were conducted for 90 days at HRT of 24 h. The results demonstrated an adequate efficiency of the UASB reactor to treat SWW of up to 94.31% for the removal of COD.

Chávez et al. (2005) evaluated the removal of BOD from SWW using 3 L UASB reactors and a 3-levels factorial design and RSM. A maximum 95% removal of BOD was obtained with OLRs up to 31000 mg/L under optimum conditions, with temperature values ranging between 25 and 39°C at HRTs between 3.5 and 4.5 h.

Miranda et al. (2005) assessed the performance of an 800-m³ UASB for SWW treatment. Influent concentrations of COD and oil and grease (O&G) were in the range of 1400-3600 and 413-645 mg/L,

respectively. Results show that the UASB performance was enhanced when influent COD/O&G ratios remained at 10%. Thus, O&G and COD removal efficiencies reached 27-58 and 70-92%, respectively.

Rajakumar and Meenambal (2008) evaluated the performance of the UASB process for SWW treatment. Influent COD concentrations varied from 3000 to 4800 mg/L. The UASB reactor showed an optimum COD removal efficiency of up to 90% at a HRT of 10 h. Moreover, results show that by reducing HRT to less than 10 h in the UASB, sludge wash out appears and lower COD removal efficiencies of less than 70% are obtained (Rajakumar et al., 2012).

Mijalova Nacheva et al. (2011) analyzed the performance of a UASB reactor under ambient conditions for SWW treatment after solid separation. COD removal efficiencies increased proportionally to OLRs. Thus, COD removal efficiencies of up to 90% were obtained with the influent COD concentrations of 3437 mg/L. Although UASB reactors are found to be efficient for SWW treatment, a posttreatment is required to comply with current water quality standards for water body discharge.

3.4.4.2. Aerobic treatment

In aerobic systems, aerobic bacteria are accountable for the removal of organic materials in the presence of oxygen. The treatment time and the amount of required oxygen increase suddenly with the strength of SWW. Aerobic treatment is commonly used for final decontamination and removal of nutrients after using physicochemical or anaerobic techniques (Chernicharo, 2006). Aerobic reactors may have several configurations. However, the biological process is very similar, and being necessary to define if nitrogen removal is required (San José, 2004). Typical configurations for SWW aerobic treatment include activated sludge (AS), rotating biological contactors (RBCs), and aerobic SBR.

3.4.4.2.1. Activated sludge process

AS is an aerobic treatment method that brings the effluent into contact with air and free-floating flocs of microorganisms including bacteria and protozoa. The AS process has been widely applied in different industries as a commonly known cost-effective method for the treatment of SWW. The purpose of the AS process is to remove soluble and insoluble organics from the wastewater and to change this material into a flocculent microbial suspension that is then settled in a clarifier. Two distinct mechanisms are applied in AS, adsorption and oxidation of the organic matter (Bull et al., 1982; Al-Mutairi, 2008). A typical AS system is depicted in Figure 3.3.

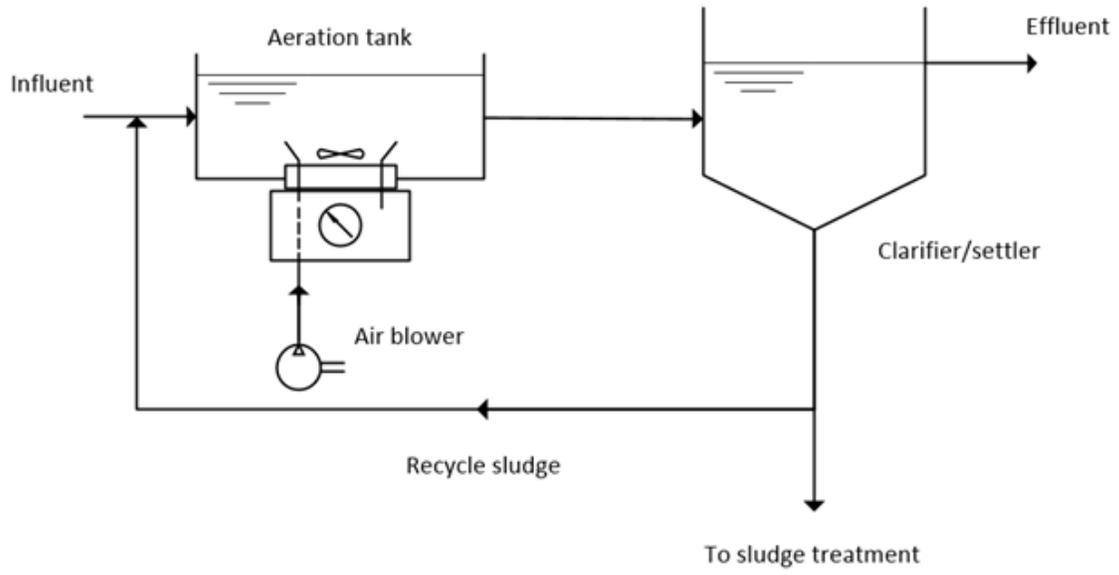


Figure 3.3. Schematic diagram of a typical activated sludge system.

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AS systems, treating SWW, produce poor settling flocs because of fats present in SWW influents and low dissolved oxygen (DO) levels. Design criteria of the AS process for SWW treatment require extended aeration to minimize the sludge production. The HRT are longer than that of typical municipal wastewater treatment plants to guarantee a sludge age in the range of 5-20 days, recommended for SWW treatment (Johns, 1995).

Pabón and Gélvez (2009) evaluated the performance of a 144m³ full-scale AS reactor for SWW treatment. The average treated flow was 1.38 L/s with a 2-day HRT. Oxygen was injected using a high-efficiency air equipment. Bulk SWW parameters, including BOD, COD, and TSS with an influent concentration of 5242, 9040, and 2973 mg/L, respectively, were evaluated. Maximum removal efficiencies of 94.09, 89.73, and 89.03% were achieved for TSS, BOD, and COD, respectively.

Fongsatitkul et al. (2011) examined the performance of the AS system to treat SWW. Two 10 L continuous-flow reactors running in parallel with internal recycle (IR) were used. The COD removal efficiency reached up to 97.60%, the total Kjeldahl nitrogen (TKN) removal rate ranged from 81.50 to 95.60%, and the TP removal reached its maximum around 85-89%.

Hsiao et al. (2012) evaluated different kinetic parameters for an AS reactor treating SWW using the Monod equation and compared to the data obtained from the experiment. The AS system at the temperature of 26°C removed up to 97.20% of COD from SWW. Predicted values were validated by the experimental values. The sensitivity analysis indicated that the COD residual concentration was highly sensitive to the variation of the maximum specific substrate utilization rate, producing a noticeable COD intensification.

Carvalho et al. (2013) aimed to evaluate the role of AS process in the removal of veterinary drugs including enrofloxacin, tetracycline, and ceftiofur from SWW in batch reactors. Sludge bioreactors with initial pharmaceutical concentrations of 100 g/L presented removal rates of 68% for enrofloxacin and 77% for tetracycline from the aqueous phase. Results showed that sorption to wastewater organic content and biomass was accountable for a significant fraction of the pharmaceuticals removal. Nevertheless, these removal rates are still low for effluent discharge. Therefore, it is required to consider alternative methods for treating this effluent such as AOPs.

Bustillo-Lecompte et al. (2013, 2014) evaluated the effectiveness, performance, and costs of an AS reactor for the treatment of SWW using a CEA. The aerobic AS reactor obtained the best performance under TOC and TN influent concentrations of 1009 and 254 mg/L with up to 95.03% TOC and 73.46% TN removals, respectively. At higher influent TOC and TN concentrations, the TOC and TN removal are higher. For an influent concentration of 639 mgTOC/L and 144 mgTN/L, TOC removals reached 89.66% and TN removals reached 43.19% at HRT of 5 days, whereas at 8 days, TOC removals reached 94.26%, and TN removals reached 75.15%. On the other hand, by means of the CEA, it was found that the AS process is an efficient process with optimum TOC removal of up to 88% at a cost of 4 \$/kg of TOC removed. Thus, if low or intermediate amounts of TOC are to be removed, the AS process is comparable to combined processes in economic terms.

3.4.4.2.2. Rotating biological contactor

The RBC process allows the wastewater to be exposed to a biological medium in order to absorb and metabolize the organic content as well as to remove other pollutants before discharge to the environment (Mittal, 2006). However, the performance of an RBC to treat SWW has been reported as inadequate in literature (Bull et al., 1982; Johns, 1995) compared to conventional aerobic treatment systems such as the AS process.

Torkian et al. (2003) investigated the performance of a 6-stage RBC pilot plant for post-treatment of SWW. The overall removal efficiencies for BOD and COD decreased by increasing the OLR. Results indicated successful post-treatment of SWW to meet regulatory requirements with a BOD removal efficiency of up to 88%. On the other hand, Al-Ahmady (2005) studied the COD removal in RBC systems as a function of the OLR. A wide range of COD removal of 40-85% can be obtained when treating SWW by RBCs because of the specific OLR applied, especially during the first stages of the system.

3.4.4.2.3. Aerobic sequencing batch reactor

In an aerobic SBR, there are five stages including filling, reaction, settling, decanting/drawing, and idle. In the first stage, the feed enters the reactor while mixing is provided by mechanical means in the absence of air (anoxic phase). Then, the aeration of the mixed liquor is executed for the reactions to occur (aerobic phase). During the third stage, the TSS start to settle since there is no aeration or mixing. During the fourth stage, the clean supernatant liquor exits the tank as the effluent.

Filali-Meknassi et al. (2005a; 2005b) studied the performance of an aerobic SBR for SWW treatment with influent concentrations of 5000 mgCOD/L and 360 mgTN/L. Overall efficiencies were achieved for COD and TN in the range 95–96% and 95–97%, respectively. Likewise, Lemaire et al. (2008, 2009) evaluated the performance of SBRs under six-hour cycles for SWW treatment. High efficiencies for COD, TP, and TN removal of 95, 98, and 97% were achieved, respectively.

Conversely, Li et al. (2008) assessed the influence of the aeration rate on organics and nutrients removal from SWW using two laboratory-scale SBRs operated at ambient temperature for 8 h. The influent concentrations of TN and COD were 350 and 4000 mg/L, respectively. Results show that at higher aeration rates, the TN removal efficiency increases considerably. For instance, at an aeration rate of 0.4 L/min, TN and COD removal efficiencies reached 34 and 90%, respectively. Conversely, aeration rates above 0.8 L/min permitted removal efficiencies of up to 97 and 95% for COD and TN, respectively.

Zhan et al. (2009) examined the TN removal from SWW in a SBR at laboratory-scale using two aeration strategies, intermittent and continuous, at low DO range. Under the intermittent aeration strategy, the maximum DO was fixed at 10% saturation. On the other hand, under the continuous aeration strategy, the DO was maintained at 10% saturation during the first hour of the reaction phase, and then at 2% for the remaining reaction phase. TN removals of 91 and 95% were accomplished by continuous and intermittent aeration, respectively. Therefore, an on-site measurement of DO levels can be used to regulate the SBR operation in order to improve TN removal.

Mees et al. (2011, 2014) used a 5-L aerobic SBR with suspended biomass for the removal of organics and nutrients from SWW. Optimal conditions were obtained by a central composite design (CCD) at 16-h cycles. 20 cycles were completed to investigate the kinetics for the degradation of COD and TN. Up to 85.91% and 62.13% removal efficiencies were achieved for TN and COD, respectively.

Kundu et al. (2013, 2014) evaluated the performance of a SBR for the removal of TN and COD from SWW at laboratory-scale. Influent concentrations of TN and COD were 90e180 and 950-1050 mg/L, respectively. Results showed a COD removal of up to 95% at 8 h. A reasonable degree of nitrification between 74.75 and 90.12% was achieved for TN influent concentrations of 176.85 and 96.58 mg/L, respectively. Kinetic coefficients were also determined.

Pan et al. (2014) evaluated the removal of TN from SWW at low temperatures of up to 11°C through partial nitrification-denitrification, by means of an 8-L SBR. The influent concentration of the SWW contained COD, TN, TP, and TSS concentrations of 6068, 571, 51, 1800 mg/L, respectively. OLRs of up to 610 mgCOD/L day were used at cycles of 12 h. The optimum aeration rate was found to be 0.6 L/min at maximum TP, COD, and TN removal efficiencies of 96, 98, and 98%, respectively.

3.4.4.3. Constructed wetlands

CWs are an attractive alternative to conventional wastewater treatment, especially in rural areas since the biological treatment is a cost-effective method (Chan et al., 2009; Oller et al., 2011; Bustillo-Lecompte et al., 2014). This is due to low O&M costs, simplicity in design, and relatively few impacts on the environment. CWs simulate the mechanisms of natural wetlands for water purification, combining biological, physical, and chemical processes that occur when microorganisms, soil, atmosphere, plants, and water interact. This interaction results in the appearance of sedimentation, filtration, adsorption, biodegradation, photosynthesis, photo-oxidation, and subsequent organics and nutrients uptake by the system.

Gutiérrez-Sarabia et al. (2004) studied a full-scale constructed subsurface-flow wetland system. The CW accounted for 30% of the organic matter removal in the system. Although the treatment system achieved satisfactory pollutant removals of 91, 89, and 85% for BOD₅, COD, and TSS, respectively, the final effluent could not meet local standards. Moreover, the TP removal was null.

Soroko (2007) evaluated the performance of CW systems for the treatment of SWW. Two vertical flow constructed wetlands (VFCWs) and one horizontal flow constructed wetland (HFCW) were used. The SWW influent had average concentrations of 3188, 2500, and 500 mg/L for COD, BOD, and TN, respectively. Results showed that sand and gravel beds of CWs could be effective in removal of organic substances, up to 97.40, 99.90, and 78.20% of COD, BOD, and TN from the SWW influent, respectively.

Carreau et al. (2012) constructed a CW with *Typha latifolia* for the treatment of SWW with HRT of 111 days and 89% active volume. Up to 95, 72, 88, and 87% removal efficiencies were achieved for BOD, TSS, TP, and TN, respectively. Likewise, Odong et al. (2013) investigated different CWs for the treatment of SWW with influent concentrations of COD, BOD, and TN in the ranges of 293-314, 79-87,

and 56-64 mg/L, respectively. Results showed a broad range of removal for different vegetation. COD, BOD, and TN removal rates ranged from 28.28 to 75.03, 9.27 to 71.40, and 5.20 to 25.40%, respectively.

3.4.5. Advanced oxidation processes

AOPs are becoming an interesting alternative to conventional treatment and a complimentary treatment option, as either pre-treatment or post-treatment, to current biological processes. Furthermore, AOPs may inactivate microorganisms without adding additional chemicals to the SWW in comparison to other techniques such as chlorination that are commonly used in water disinfection, thus, avoiding the possible formation of hazardous by-products (De Sena et al., 2009; Bustillo-Lecompte et al., 2015). Therefore, AOPs have come handy to be recognized as advanced degradation, water reuse, and pollution control processes showing excellent overall results as complimentary treatment (Tabrizi and Mehrvar, 2004; Mehrvar and Venhuis, 2005; Venhuis and Mehrvar, 2005; Mehrvar and Tabrizi, 2006; Edalatmanesh et al., 2008; De Sena et al., 2009; Cao and Mehrvar, 2011; Barrera et al., 2012; Mohajerani et al., 2012; Bustillo-Lecompte et al., 2013, 2014; Hamad et al., 2014; Mowla et al., 2014; Ghafouri et al., 2015).

Millamena (1992) used Ozonation technology for the treatment of SWW. Results showed that the utilization of a low concentration ozone stream of 110 mg/h for the removal of the majority of organics in slaughterhouse wastewater was not feasible. With pre-treatment, the overall efficiency of ozonation in terms of BOD removals was in the order of 42%, TOC reached 34% removal, and better removal was attained with COD at 58%.

Wu and Doan (2005) also used Ozonation for the treatment of SWW. Results show that ozone was effective in disinfecting SWW after 8 min using an ozone dosage of up to 23.09 mg/min per L. Up to 99% of microorganisms were inactivated. Nevertheless, the COD and BOD removal were only 10.70 and 23.60%, respectively.

Melo et al. (2008) evaluated gamma radiation (GR) for the treatment of SWW. Low COD, BOD, and TSS efficiency removals were obtained at a dose rate of 0.9 kGy/h. Nevertheless, a decrease of BOD in the range of 38.65-85.75% was observed at high-absorbed irradiation dosages (25 kGy/h). Although the results obtained at high doses, the costs associated with this technology are its main drawback.

The UV/H₂O₂ process is one of the most widely used AOPs. The UV/H₂O₂ process has been found to be effective for SWW treatment. Oxidation and degradation of pollutants by UV/H₂O₂ rely on hydroxyl radicals ([•]OH), a highly reactive species produced from the reaction of the H₂O₂ with the UV light (Tabrizi and Mehrvar, 2004; Mehrvar and Tabrizi, 2006; Edalatmanesh et al., 2008; De Sena et al., 2009; Luiz et al., 2009; Cao and Mehrvar, 2011; Barrera et al., 2012; Mohajerani et al., 2012; Hamad et al., 2014; Mowla et al., 2014; Bustillo-Lecompte et al., 2015; Ghafoori et al., 2015). A schematic diagram of a single lamp UV/H₂O₂ photoreactor system is presented in Figure 3.4.

Luiz et al. (2009) evaluated the UV/H₂O₂ process for the treatment of a secondary SWW effluent. Results show that the UV/H₂O₂ treatment was more effective than conventional UV alone in removing organic matter. The UV/H₂O₂ process was five times more rapidly in degrading aromatics than UV only. Up to 95% in COD removal efficiency was reached after 5 h of treatment.

De Sena et al. (2009) studied the effectiveness of AOPs for the treatment of SWW using UV/H₂O₂ and photo-Fenton in a laboratory scale. Results showed that the AOPs increased the removal of organics from pre-treated SWW samples with overall COD and BOD removal rates of up to 97.60 and 95.70%, respectively. Thus, AOPs might be considered to enhance SWW effluents quality for water reuse purposes.

Cao and Mehrvar (2011) evaluated a UV/H₂O₂ photoreactor as the post-treatment of a synthetic SWW at a laboratory scale. A TOC influent concentration of 157.6 mg/L was used. Up to 84, 64, and 83% of BOD, TOC, and COD removals, respectively, were obtained at HRTs of 2.5 h with a H₂O₂ dosage of 529 mg/L. The H₂O₂ dosage of 3.5 mgH₂O₂/h per mg TOC in the influent was found to be the optimum for the UV/H₂O₂ process.

The degradation of TOC and microorganism disinfection from synthetic SWW secondary effluents were investigated by Barrera et al. (2012) using UV-C and vacuum-ultraviolet (VUV). TOC removals ranged from 5.5 to 12.2% for UV-C/H₂O₂ and VUV/H₂O₂, respectively. Optimum H₂O₂/TOC molar ratios of 1.5 and 2.5 were found for VUV and UV-C, respectively. Furthermore, it was discovered that the photochemical processes were capable of rapid bacteria inactivation in less than 30 seconds.

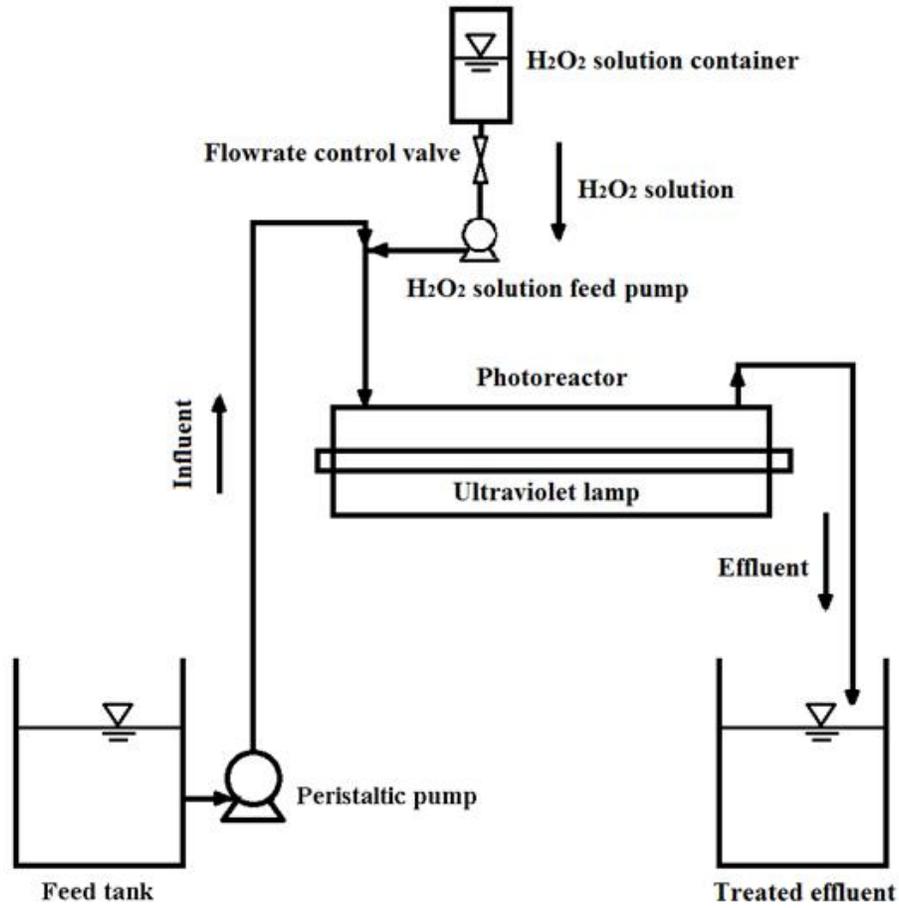


Figure 3.4. Schematic diagram of a single lamp UV/H₂O₂ photoreactor.

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Bustillo-Lecompte et al. (2013) evaluated the performance of the UV/H₂O₂ process for the SWW treatment. TOC loadings of up to 350 mg/L were used in the SWW influent. An optimum TOC removal of 75% was obtained for influent concentrations of up to 65 mgTOC/L and HRTs of 180 min with H₂O₂ dosages of 900 mg/L. An optimum molar ratio dosage of 14.03 mgH₂O₂/mgTOC_{in} was also found for the UV/H₂O₂ process.

Bustillo-Lecompte et al. (2014) compared the UV/H₂O₂ alone to other treatment technologies to treat SWW as an individual method. The UV/H₂O₂ alone was found to be the least efficient process with optimum removals of up to 50% at a cost of 67 \$/kg of TOC removed. Moreover, the TOC removal was not significantly increased by augmenting the HRT. Therefore, although the UV/H₂O₂ process is effective to treat the SWW, the UV/H₂O₂ is expensive if applied alone. Consequently, SWW treatment by the combination of AOPs and biological processes is recommended while they are optimized at an appropriate residence time in each reactor.

3.4.6. Combined processes

SWW effluents are part of the food and beverage industry wastewaters (Oller et al., 2011; Vymazal, 2014; Valta et al., 2015). SWWs are one of the major concerns of the agro-industrial sector because of the high amounts of water used in the process of slaughtering and further cleaning of the facilities (De Sena et al., 2009; Oller et al., 2011; Valta et al., 2015).

It may be stated that it is beneficial, in terms of operation and economics, to implement combined processes for the treatment of SWW since it couples the benefit of different technologies to improve high strength industrial wastewater management (Kuşçu and Sponza, 2006; Ahn et al., 2007; Chan et al., 2009; Bazrafshan et al., 2012; Cao and Mehrvar, 2011; Barrera et al., 2012; Bazrafshan et al., 2012; Bustillo-Lecompte et al., 2013, 2014).

Del Pozo and Diez (2005) evaluated a combined anaerobic-aerobic fixed-film reactor for SWW treatment under sub-mesophilic conditions (25°C). Overall COD removals of up to 93% were obtained for OLRs of 0.77 kg/m³ day, along with TN removals of up to 67% for a TN influent load of 0.084 kg N/m³ day. Denitrification only implied 12-34% of the TN removal being limited by DO levels above 0.5 mg/L in the anaerobic section.

Bohdziewicz and Sroka (2005) considered combined AS-RO system for the treatment of SWW. The raw SWW was first pretreated using activated sludge (AS). Results showed a high removal of contaminants from the SWW by the combined processes, including COD (99.80%), BOD (99.83%), TP (99.76%), and TN (99.77%).

Mahtab et al. (2009) evaluated a combined coagulation/adsorption process for SWW effluents using various coagulants, such as alum, ferrous sulfate, ferric chloride, and lime. Results show that optimum COD removal efficiencies of up to 92% are obtained by using alum as the coagulant. Nevertheless, it was concluded that the combined coagulation/adsorption process made not significant improvement in COD removal from SWW.

A laboratory scale anaerobic-aerobic system, consisting of an AF attached to an aerobic SBR, was used for SWW treatment (López- López et al., 2010). The AF operated with OLR in the range of 3.7-16.5 kg/m³ day and at HRTs of up to 72 h. Up to 81% COD removals were obtained and was found to be inversely correlated to OLRs. When coupling the AF to the SBR, over 95% COD was removed in 9 h. Moreover, optimum conditions were detected at OLRs below 11 kg/m³ day with HRT of 24 h.

On the other hand, Cao and Mehrvar (2011) evaluated the combined ABR and UV/H₂O₂ processes at laboratory scale for synthetic SWW treatment. Results showed that combined processes are more efficient than individual processes for SWW treatment. Up to 95% TOC, 98% COD, and 97% BOD removals were obtained for influent concentrations of 973 mg/L at HRTs in the ABR of up to 3.8 days and 3.6 h within the UV/H₂O₂ reactor.

Bazrafshan et al. (2012) assessed the performance of combined chemical coagulation (CC) and EC for the SWW treatment. BOD and COD removal rates were directly proportional to the applied voltage and coagulant dosage with up to 99% removal efficiencies for both parameters. As a result, the combined CC-EC processes were found to be more efficient than EC alone for SWW treatment.

Bustillo-Lecompte et al. (2013, 2014) evaluated the performance and operating costs of treating SWW using combined biological and AOPs. A comparison was made in terms of the treatment capability and overall costs for different technologies including ABR, AS, and UV/H₂O₂. Overall efficiencies reached 75.22, 89.47, 94.53, 96.10, 96.36, and 99.98% by the UV/H₂O₂, ABR, AS, combined AS-ABR, combined ABR-AS, and combined ABR-AS-UV/H₂O₂ processes, respectively. A CEA was performed

at optimal conditions for the SWW treatment by optimizing the total electricity cost, H₂O₂ consumption, and HRT. The combined ABR-AS-UV/H₂O₂ processes reached a maximum TOC removal of 99% in 76.5 h with an estimated cost of 6.79 \$/m³ day.

The combined ABR-AS-UV/H₂O₂ system was proven the most cost-effective solution compared to other processes for the TOC removal under these conditions. Nevertheless, the selection of a particular treatment method for SWW treatment requires an analysis of the characteristics of the SWW being treated and the best available technology (BAT) in order to comply with current regulations and different jurisdictions worldwide.

3.5. Summary and conclusions

A summary of the most commonly applied technologies and combined processes during the last decade is portrayed in Table 3.6, with particular attention to treatment efficiencies in terms of organic and nutrient removal, highlighting commonly used parameters, such as COD, TOC, BOD, and TN. The treatment efficiency of SWW varies extensively, it depends on several factors including, but not limited to, the characteristics of the SWW, the HRT, and the pollutant concentration in the influent. Table 3.6 also reveals that several types of individual and combined processes have been used for the SWW treatment.

SWWs are commonly pre-treated by screening, settling, blood collection, and fat separation, followed by physicochemical treatment, including DAF, coagulation/flocculation, and/or secondary biological treatment. Although the organic matter and nutrient removal can achieve high efficiencies, the treated SWW effluent usually need further treatment by membrane technologies, AOPs, or other appropriate treatment methods as combined processes. AOPs may also provide high-quality treated water allowing water recycle in the meat processing industry. Therefore, combined processes have evolved into a reliable technology that is nowadays successfully used for many types of SWW effluents. However, the selection of a specific treatment mainly depends on the characteristics of the SWW being treated, the BAT, and the compliance with current regulations under different political jurisdictions.

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Table 3.6. Comparison of different technologies and their combination for slaughterhouse wastewater treatment.

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Processes ¹	HRT ² (h)	TOC _{in} ³ (mg/L)	COD _{in} ³ (mg/L)	BOD _{in} ³ (mg/L)	TN _{in} ³ (mg/L)	TOC removal (%)	COD removal (%)	BOD removal (%)	TN removal (%)	Reference
AeP-RO	8-36	-	5,300	2,900	557	-	99.80	99.83	99.77	Bohdziewicz and Sroka (2005)
AnaP	24-2,160	3,500	1,820-12,790	-	1,176	-	71.51-94.31	-	-	Caldera et al. (2005)
AnaP	360	-	5,800-11,600	4,524-8,700	11-11,150	-	-	20.20-95.60	-	Chávez et al. (2005)
AnaP-AeP	23-91	-	1,190-2,800	610-1,150	150-260	-	93.00	97.00	69.00	Del Pozo and Diez (2005)
AeP	49	-	5,000-5,098	-	349-370	-	95.00-96.00	-	86.00-88.00	Filali-Meknassi et al. (2005a)
AeP	48	-	5,155-5,675	-	369-431	-	96.00	-	97.00-99.00	Filali-Meknassi et al. (2005b)
AnaP-AeP	249	-	3,000	-	-	-	90-92	-	-	Kuşçu and Sponza (2005)
AnaP	24-48	-	7,083	-	547	-	93.9	-	-	Masse and Massé (2005)
AnaP	18-27	-	1,400-3,600	-	13-179	-	70.60-92.60	-	-	Miranda et al. (2005)
CC	-	-	10,226-15,038	5,042-8,320	-	-	32.20-63.60	34.70-67.80	-	Satyanarayan et al. (2005)
AOP	0.13	-	-	-	-	-	10.70	23.60	-	Wu and Doan (2005)
EC	0.42	-	2,600-2,900	10,000-12,000	-	-	60.00-93.00	-	-	Bayramoglu et al. (2006)
EC	0.42	-	2,600-2,900	12,000-10,000	-	-	60.00-93.00	-	-	Kobya et al. (2006)
AnaP-AeP	249	-	3,000	-	70-147	-	80.00-99.00	-	77.40	Kuşçu and Sponza (2006)
AnaP-AeP	24	-	6,000-14,500	-	300-1,000	-	99.00	-	46.00	Ahn et al. (2007)
AnaP	-	-	3,102	-	186	-	-	-	-	Amorim et al. (2007)
AnaP	69	-	2,360-4,690	1,190-2,624	147-233	-	57.00-67.00	48.50-63.00	36.00-40.00	Del Nery et al. (2007)
AnaP	30-80	-	7,148-20,400	3,501-8,030	-	-	62.00-96.40	93.96	-	Saddoud and Sayadi (2007)
CW	-	-	3,188	2,452-2,500	494-500	-	97.40	99.90	78.20	Soroko (2007)
AeP	3.0-8.0	-	431	1,320	5.6	-	72.00	99.00	-	Al-Mutairi et al. (2008)
EC	1.0-1.5	-	1,290-1,670	2,700-3,100	-	-	82.00	86.00	-	Asselin et al. (2008)
AnaP	-	-	1,913-5,157	1,559-2,683	-	-	21.00-58.00	14.00-64.00	-	De Nardi et al. (2008)
GR	-	-	-	3,860	-	-	-	38.65-85.75	-	Melo et al. (2008)
AeP	42	-	6,400-8,320	-	260-306	-	95.00	-	97.00	Lemaire et al. (2008)
AeP	8.0	-	2,850-4,700	1,000-2,900	250-350	-	97.00	-	94.00	Li et al. (2008)
AnaP	10-3,600	1,030-3,000	3,000-4,800	750-1,890	109-325	15.00-86.00	18.00-80.00	-	-	Rajakumar and Meenambal (2008)
AnaP	60	-	4,200-9,100	-	565-785	-	72.20-98.60	-	45.90-63.70	Debik and Coskun (2009)
AeP-AOP	0.50	-	2,800-3,000	1,400-1,600	-	-	80.30-97.60	70.30-95.70	-	De Sena et al. (2009)
AnaP	48	-	5,800-6,100	-	530-810	-	80.00-92.00	-	-	Gannoun et al. (2009)
AnaP	48-240	-	2,100-2,425	-	250-260	-	88.00-99.00	-	76.00-78.00	Kabdaşlı et al. (2009)
AnaP	10	-	2,373-2,610	900-2,000	78-457	-	96.00-97.00	95.58-97.88	52.00-93.00	Kist et al. (2009)
AnaP	42	-	7,460-9,300	-	271-317	-	95.00	-	97.00	Lemaire et al. (2009)
AOP	5	-	-	-	-	-	18.00-95.00	-	-	Luiz et al. (2009)
CC-AdP	2	-	6,605	5,703	-	-	91.10-96.80	93.50-96.80	-	Mahtab et al. (2009)
AeP	29	-	9,040	5,242	-	-	89.03	89.73	-	Pabón and Gélvez (2009)
CC-AeP	0.33	-	2,000-3,000	-	100-200	-	80.00	-	90.00	Wang et al. (2009)
AeP	104	-	2,800-3,500	-	220-350	-	98.00-99.00	-	91.00-95.00	Zhan et al. (2009)
AeP	-	-	24,000	1,198	139	-	90.00	-	-	Al-Mutairi (2010)
AnaP-AeP-CC	16-72-	-	6,363-11,000	5,143-8,360	46.6-138	-	50.10-97.42	97.76-98.92	73.48-92.72	López-López et al. (2010)
AnaP	30-97	-	8,450-41,900	21,000	-	-	18.60-56.90	-	-	Marcos et al. (2010)
UF	-	-	3,610-4,180	1,900-2,200	-	-	94.52-94.74	97.80-97.89	-	Yordanov (2010)
EC	1.2	-	2,171	1,123	-	-	75.00-90.00	-	-	Bayar et al. (2011)
AnaP-AOP	76-91	80-950	2,110-2,305	1,020-1,143	80-334	89.90-95.00	97.70	96.60	1.00-6.00	Cao and Mehrvar (2011)
AnaP-AeP-UV	12	-	23-70	0.0-5.0	2.0-21	85.00	-	-	79.00	De Nardi et al. (2011)
AnaP-AeP	16	-	876-1,987	12,000	84-409	-	90.60-97.60	-	81.50-95.60	Fongsatitkul et al. (2011)

Processes ¹	HRT ² (h)	TOC _{in} ³ (mg/L)	COD _{in} ³ (mg/L)	BOD _{in} ³ (mg/L)	TN _{in} ³ (mg/L)	TOC removal (%)	COD removal (%)	BOD removal (%)	TN removal (%)	Reference
UF	720-1,344	50-328	114-1,033	-	82-127	75.00-96.00	83.00-97.00	-	27.00-44.00	Gürel and Büyükgüngör (2011)
AeP	-	-	298-1,115	-	-	-	53.65	84.32	-	Mees et al. (2011)
AnaP	12-48	-	6,500	2,900	-	-	75.00-83.00	-	-	Méndez-Romero et al. (2011)
AnaP	-	-	3,437	2,646	218	-	76-90	-	8.20-10.10	Mijalova Nacheva et al. (2011)
AnaP	12	-	3,000-4,800	750-1,890	109-325	-	70.00-78.00	-	-	Rajakumar et al. (2011)
EC	0.83	-	-	-	-	-	62.00-93.00	66.00-97.00	56.00-84.00	Ahmadian et al. (2012)
AOP	2.5	1,000	-	-	-	57.60	-	-	-	Barrera et al. (2012)
EC-CC	25	-	4159-5817	2204-2543	92-137	-	80-98	75-93	75-80	Bazrafshan et al. (2012)
AeP	12-20	-	5,220	-	4,500	-	-	-	-	Dallago et al. (2012)
AeP	110-583	-	850-1,400	-	50-100	-	93.50-97.20	-	-	Hsiao et al. (2012)
AeP-UF	48	-	1,764-2,244	1,529-1,705	435-665	91.00	98.00	-	-	Keskes et al. (2012)
AnaP	20-96	-	5,659-9,238	5,571-6,288	-	-	92.10-96.60	98.00-98.78	-	Park et al. (2012)
CC	3.0	-	6,970	5,820	-	-	85.46-92.00	85.40	-	Tariq et al. (2012)
AnaP	8.0-24	-	3,000-4,800	750-1,890	-	-	70.00-86.00	-	-	Rajakumar et al. (2012)
AnaP	794-3,948	-	70,673	-	-	-	54.00-98.00	-	-	Affes et al. (2013)
AnaP-AeP	24	-	418	117	169	-	95.00	-	76.00	Barana et al. (2013)
AnaP-AeP-AOP	75-168	941-1,009	-	630-650	254-428	89.50-99.90	-	99.70	76.40-81.60	Bustillo-Lecompte et al. (2013)
AeP	240	0.10	150	-	-	-	68.00-77.00	-	-	Carvalho et al. (2013)
AeP	1.0	-	18,200	10,500	-	-	81.31-93.08	-	-	Hossaini et al. (2013)
AeP	48	1,152-1,312	2,052-2,296	1,529-1,705	435-665	-	89	-	-	Keskes et al. (2013)
AOP	0.42	2,240	-	-	290	92.60	-	-	76.20	Khennoussi et al. (2013)
AeP-AnaP	8.0	-	6,485-6,840	3,000-3,500	1,050-1,200	-	95.00	-	97.00	Kundu et al. (2013)
AeP	23	-	5,590-11,750	3,450-4,365	214-256	-	74-94	-	-	Louvet et al. (2013)
AnaP	39-72	-	1,040-24,200	-	296-690	-	30	-	-	McCabe et al. (2013)
AnaP	172	-	1,790-4,760	834-3,186	90-196	-	79.00-89.00	84.00-94.00	-	Nery et al. (2013)
CW	-	-	293-3,141	79-87	52-64	-	28.28-75.03	9.27-71.40	5.20-25.40	Odong et al. (2013)
AnaP	24-36	-	2,273-20,073	-	570-1,603	-	51.00-72.00	-	3.50-21.60	Siqueira et al. (2013)
EC	1.0	-	2,171	1,123	148	-	69.00-83.00	-	-	Bayar et al. (2014)
AnaP-AeP-AOP	41-76	100-1,200	-	610-4,635	50-841	75.22-99.98	-	-	-	Bustillo-Lecompte et al. (2014)
EC	1.5	-	840	-	-	-	90.00	-	-	Eryuruk et al. (2014)
EC	-	-	-	-	-	-	55.00-60.00	-	-	Hernández-Ramírez et al. (2014)
AeP	3.0-96	-	6,185-6,840	-	1,950-3,400	-	9.42-80.11	-	8.81-93.22	Kundu et al. (2014)
AeP-AnaP	888	-	1,400-2,500	-	200-250	-	30.20-98.68	-	22.40-96.16	Li et al. (2014)
AnaP	24	-	49-137	30-76	6.1-27	-	13.90	11.30	42.30-77.20	Manh et al. (2014)
AnaP	46-72	-	12,000-15,800	-	-	-	60.00	-	-	Martinez et al. (2014)
AnaP	48-72	-	1,014-12,100	1,410-7,020	-	-	83.62	94.23	-	McCabe et al. (2014)
AOP	0.04-1.0	-	3,337-4,150	1,950-2,640	-	-	76.70-90.70	-	-	Ozyonar and Karagozoglu (2014)
AeP	12-3,360	1,435	6,057-6,193	4,214-4,240	547-576	-	97.80-98.20	-	97.70	Pan et al. (2014)
AeP	12-16	-	356-384	-	143-175	-	-	-	80.76-91.09	Mees et al. (2014)
AnaP	24-480	-	88	-	-	-	67.00-80.00	-	90.00	Stets et al. (2014)
AnaP	2,640	-	18,600	-	5,200	-	-	-	28.00-65.80	Yoon et al. (2014)
MF	-	183	480	-	115	44.81	90.63	-	45.22	Almandoz et al. (2015)
AnaP-MF	48-168	470-2,778	2,084-13,381	-	108-295	86.36-95.11	97.17-98.90	-	78.00-90.00	Jensen et al. (2015)

¹ AC, activated carbon; AdP, adsorption process; AeP, aerobic process; AnaP, anaerobic process; AOP, advanced oxidation process; CC, chemical coagulation; CW, constructed wetland; EC, electrocoagulation; GR, gamma radiation; MF, microfiltration; RO, reverse osmosis; UF, ultrafiltration; UV, ultraviolet light.

² HRT, Hydraulic retention time.

³ TOC_{in}; COD_{in}; BOD_{in}; TN_{in}, influent concentration of total organic carbon, chemical oxygen demand, biochemical oxygen demand, and total nitrogen, respectively.

CHAPTER 4

COST-EFFECTIVENESS ANALYSIS OF TOC REMOVAL FROM SLAUGHTERHOUSE WASTEWATER USING COMBINED ANAEROBIC-AEROBIC AND UV/H₂O₂ PROCESSES*

Abstract

The objective of this study is to evaluate the operating costs of treating slaughterhouse wastewater (SWW) using combined biological and advanced oxidation processes (AOPs). This study compares the performance and the treatment capability of an anaerobic baffled reactor (ABR), an aerated completely mixed activated sludge reactor (AS), and a UV/H₂O₂ process, as well as their combination for the removal of the total organic carbon (TOC). Overall efficiencies are found to be up to 75.22, 89.47, 94.53, 96.10, 96.36, and 99.98% for the UV/H₂O₂, ABR, AS, combined AS-ABR, combined ABR-AS, and combined ABR-AS-UV/H₂O₂ processes, respectively. Due to the consumption of electrical energy and reagents, operating costs are calculated at optimal conditions of each process. A cost-effectiveness analysis (CEA) is performed at optimal conditions for the SWW treatment by optimizing the total electricity cost, H₂O₂ consumption, and hydraulic retention time (HRT). The combined ABR-AS-UV/H₂O₂ processes have an optimal TOC removal of 92.46% at an HRT of 41 h, a cost of \$1.25/kg of TOC removed, and \$11.60/m³ of treated SWW. This process reaches a maximum TOC removal of 99% in 76.5 h with an estimated cost of \$2.19/kg TOC removal and \$21.65/m³ treated SWW, equivalent to \$6.79/m³ day.

Keywords: Cost-effectiveness analysis (CEA), slaughterhouse wastewater (SWW), activated sludge (AS), advanced oxidation processes (AOPs), UV/H₂O₂, TOC.

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4.1. Introduction

Slaughterhouse wastewater (SWW) is considered detrimental worldwide due to its composition, characterized mostly by a complex mixture of fats, proteins, and fibers (Johns, 1995; Muñoz, 2005). Wastewaters from slaughterhouses and meat processing plants (MPPs) have been considered as an industrial wastewater in the category of agricultural and food industries (Seif and Moursy, 2001). It has been classified as one of the most harmful wastewaters to the environment by the United States Environmental Protection Agency (US EPA, 2004). The effluent discharge from slaughterhouses causes deoxygenation of rivers (Quinn and McFarlane, 1989) and contamination of groundwater (Massé and Masse, 2000a).

The organic matter concentration in SWW is usually high and the residues are moderately solubilized, leading to a highly polluting effect (Ruiz et al., 1997). They usually contain high levels of organics, pathogenic and non-pathogenic viruses and bacteria, and detergents and disinfectants used for cleaning activities (Debik and Coskun, 2009). High concentrations of biochemical oxygen demand (BOD), chemical oxygen demand (COD), total organic carbon (TOC), total nitrogen (TN), and total suspended solids (TSS) in SWW containing flesh and blood have been reported to be 4635, 15900, 1200, 841, and 2800 mg/L or more, respectively (Tritt and Schuchardt, 1992; Massé and Masse, 2000b). Several studies have described the common characteristics of SWW (Gariépy et al., 1989; Seif and Moursy, 2001; Cao and Mehrvar, 2011; Wu and Mittal, 2011; Barrera et al., 2012; Bustillo-Lecompte et al., 2013). These characteristics are summarized in Table 4.1, in which their common ranges and averages of COD, TOC, BOD, TSS, TN, and pH for SWW are presented.

Table 4.1. Common characteristics of slaughterhouse wastewater.

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Parameter	Range	Average
TOC (mg/L)	100–1,200	546
BOD (mg/L)	610–4,635	1,209
COD (mg/L)	1250–15,900	4,221
TN (mg/L)	50–841	427
TSS (mg/L)	300–2,800	1,164
pH	4.90–8.10	6.95

Commonly, research on wastewater treatment includes the study of different contaminants, the effects of operating variables, and the efficiency of the processes. Nevertheless, there are limited studies on the economic information and analysis, reaction mechanisms, and kinetic modeling that may help to estimate the costs of different technologies for scale-up and industrial applications (Durán et al., 2012; Benedetti et al., 2013; Ghafoori et al., 2012, 2013, 2014a). The operational costs considered in the cost-effectiveness analysis (CEA) are those related to the electrical energy consumption, the chemical consumption, and the replacement of UV lamps.

The objectives of this study are to evaluate the effectiveness and performance of the ABR, AS, and UV/H₂O₂ processes, as well as their combination for the treatment of SWW using a CEA in order to determine the best and optimal alternative method of treatment by evaluating the total electricity cost, the effects of the HRT, the cost of H₂O₂ consumption, and the removal percentage of TOC. The results obtained from this study help to extend the information on combined biological and advanced oxidation processes, their performance, and effectiveness on removing organic contaminants from SWW.

4.2. Experimental methods and procedures

Six different systems for the treatment of SWW were evaluated in this study, including UV/H₂O₂, AS, ABR, combined ABR-AS, combined AS-ABR, and combined ABR-AS-UV/H₂O₂ processes. The performance of these systems was analyzed in the previous study through the measurements of the removal efficiencies of TOC (Bustillo-Lecompte et al., 2013).

A summary of different processes compared in this study is shown in Table 4.2. This table also includes a short description of installations and optimal operating conditions. A CEA was used to determine the best alternative for SWW treatment from six different systems evaluated in this economic study including UV/H₂O₂, AS, ABR, combined ABR-AS, combined AS-ABR, and combined ABR-AS-UV/H₂O₂ processes. The economic analysis was carried out by analyzing the removal of TOC in the SWW since the degradation rate with respect to TOC is directly proportional to the rate of electricity used (Bolton et al., 2001). According to APHA (1998), the TOC analysis may be more suitable for determining organic matter content since it takes into account all of its different oxidation states. Moreover, TOC analysis provides a more accurate appraisal of the total organic compounds present in a water/wastewater sample in comparison to BOD or COD, without producing any toxic analytical

waste (Dubber and Gray, 2010). The TOC can be quantified by measuring the CO₂ generated when the organic compounds are oxidized. Thus, TOC analysis excludes the inorganic carbon compounds in order to obtain more accurate results of the organic contamination in source water.

Table 4.2. Technical conditions for the biological systems and AOPs.

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Process	Volume (L)	No. of Pumps	HRT (h)	H₂O₂ consumed (L)	TOC removal (%)
UV/H ₂ O ₂	1.35	1	3	0.094	75.22%
ABR	33.7	1	168	n/a	89.47%
AS	12	1	168	n/a	94.53%
AS-ABR	45.7	2	150	n/a	96.10%
ABR-AS	45.7	2	150	n/a	96.36%
ABR-AS-UV/H ₂ O ₂	47.05	3	96	0.2814	99.98%

The total cost of each wastewater system was calculated by adding the operating and maintenance (O&M) costs as well as the power consumption for each process. The O&M consisted of the part replacement, chemical, and electrical costs. Consistent with Bolton et al. (2001), costs related to installation and commissioning were not considered in this analysis because the industry and potential users will be able to have a standardized procedural basis for comparison. For UV systems, the operation and maintenance costs include changing lamps every 3000 h of service and chemical costs of 2.50 \$/L for consumables such as H₂O₂. The rates of H₂O₂ and electrical consumptions for different devices used for calculating the costs are shown in Table 4.3 with a common TOC concentration in the SWW influent of 1000 mg/L. According to the Ontario Energy Board (OEB, 2013), the market price of electricity based on tiered prices in August 2013 was 0.091 \$/kWh. The power consumption was calculated for each process based upon the power consumed in a year multiplied by the electricity rate as follows (Bolton et al., 2001):

$$J = E_r \left(\frac{1000Pt}{V(S_{ib} - S_f)} \right) \quad (4.1)$$

where,

E_r = energy rate (\$/kWh)

J = electricity cost (\$/kg)

P = power rating of system (kW)

S_{in} = concentration of limiting substrate in influent (mg/L)

S_f = concentration of limiting substrate in effluent (mg/L)

t = hydraulic retention time (h)

V = total reactor volume (L)

Table 4.3. Electric power and costs of electricity and H₂O₂.

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Item	Electric Power (kW)
<i>UV/H₂O₂</i>	
Lamp	0.125
Pump	0.08
Mini-pump for H ₂ O ₂ dosage	0.007
<i>Power Rating</i>	<i>0.212</i>
<i>ABR</i>	
Pump	0.08
<i>Power Rating</i>	<i>0.08</i>
<i>AS</i>	
Pump	0.08
Diffuser	0.12
<i>Power Rating</i>	<i>0.2</i>
<i>Combined ABR-AS</i>	
Pumps	0.16
Diffuser	0.12
<i>Power Rating</i>	<i>0.28</i>
<i>Combined AS-ABR</i>	
Pumps	0.16
Diffuser	0.12
<i>Power Rating</i>	<i>0.28</i>
<i>Combined ABR-AS-UV/H₂O₂</i>	
Lamp	0.125
Pumps	0.24
Diffuser	0.12
mini-pump for H ₂ O ₂ dosage	0.005
<i>Power Rating</i>	<i>0.49</i>

Note: Energy Cost (Ontario Energy Board 2013: 0.091 \$/kWh); H₂O₂ Cost = 2.50 \$/L

4.2.1. Degradation kinetics of TOC in ABR

The kinetic model Equation (4.2) developed by Kennedy and Barriault (2007) describes the limiting substrate concentration driving force within different compartments of an ABR without recycling. Thus, the first order rate constant could be calculated from operational treatment data knowing the limiting substrate concentrations and biomass in each compartment.

$$S_i = \frac{S_{i-1}}{(1 + k_i X_i V_i t / V)} \quad (\text{for } i \geq 1) \quad (4.2)$$

where,

k_i = first order rate coefficient of limiting substrate in compartment i of the ABR

S_i = concentration of limiting substrate in compartment i of the ABR (mg/L)

S_{i-1} = limiting substrate concentration in compartment $i-1$ of the ABR, ($S_{i-1} = S_{in}$ for $i-1 = 0$)

V_i = volume of compartment i in ABR (L)

X_i = biomass concentration of limiting substrate in compartment i of the ABR (mg/L)

4.2.2. Degradation kinetics of TOC in AS

The kinetic model Equation (4.3) developed by Reynolds and Yang (1966) for the completely mixed activated sludge process is based on growth relationships and material balances on the limiting substrate and biological cell mass. This equation was used to predict the effluent concentrations of TOC in the AS reactor.

$$S_f = \frac{S_{in}}{(1 + K \bar{X} t)} \quad (4.3)$$

where,

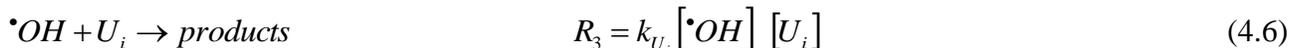
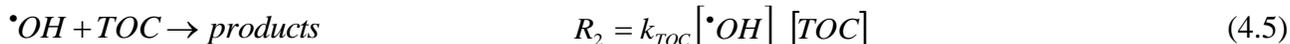
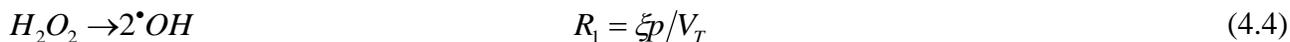
K = first order rate coefficient of limiting substrate

\bar{X} = biomass concentration of limiting substrate (mg/L)

4.2.3. Degradation kinetics of TOC in UV/H₂O₂ process

According to Bolton et al. (2001), the overall kinetics in terms of the rate of removal of a specific component, including TOC, can often be described by simple rate expressions that are either zero-order

or first-order. In general, most processes involved in AOPs, such as UV/H₂O₂, can be modeled by the following simple mechanisms:



where,

ξ = constant that depends on the type of AOP (mg/h.W)

k_{TOC} and k_{U_i} = second-order rate constants (L/mg.h)

p = power rating for system (W)

R_1 = reaction rate of $\cdot OH$ (mg/L.h)

R_2 = reaction rate of $\cdot OH$ with TOC (mg/L.h)

R_3 = reaction rate of $\cdot OH$ with a scavenger (U_i) (mg/L.h)

U_i = a scavenger for $\cdot OH$, where $i = a, b, \dots, n$ (mg/L)

V_T = treated SWW volume (L)

A steady-state analysis of this general mechanism yields the overall reaction rate for the UV/H₂O₂ process as shown in Equation (4.7). This simple mechanism is either zero or first-order in TOC. If the concentration of TOC is high ($k_{TOC} [TOC] \gg \sum_i k_{U_i} [U_i]$), the reaction rate is zero-order in TOC as shown in Equation (4.8). On the other hand, if the concentration of TOC is low ($k_{TOC} [TOC] \ll \sum_i k_{U_i} [U_i]$), the reaction rate is first-order in TOC with observed rate constant k'_{TOC} as shown in Equation (4.9). According to Bolton et al. (2001), the difference between “high” and “low” concentrations varies considerably with the system but is often approximately 100 mg/L.

$$-\frac{d[TOC]}{dt} = \frac{\xi p k_{TOC} [TOC] / V_T}{k_{TOC} [TOC] + \sum_i k_{U_i} [U_i]} \quad (4.7)$$

$$-\frac{d[TOC]}{dt} = \frac{\xi p}{V_T} \quad (4.8)$$

$$k'_{TOC} = \frac{\xi p k_{TOC}}{V_T \sum_i k_{U_i} [U_i]} \quad (4.9)$$

Therefore, Equation (4.8) was used to predict the effluent TOC concentrations from the UV/H₂O₂ process alone because of the high concentration in the influent (>1000 mg TOC/L). Likewise, due to expected TOC concentrations of less than 100 mg/L, Equation (4.9) was used to predict the effluent concentrations of TOC for the UV/H₂O₂ process as a post-treatment in combined processes.

4.3. Results and discussion

Figure 4.1 shows the comparison of six treatment methods in terms of mineralization capacity, measured in grams of TOC removed as a function of operating time. Initial conditions of the experiments included a TOC concentration in the influent of 1000 mg/L and a flow rate of 5.90 mL/min. It can be observed that combined ABR-AS-UV/H₂O₂ processes were more technically efficient than the other processes because they could remove 15% more TOC during the same operating time. Still, this apparent advantage must be confirmed in economic terms.

4.3.1. TOC degradation in ABR

The first order rate constant in each compartment in the ABR was calculated by Equation (4.2). Thus, the mass balances for all five compartments of the ABR are shown in the following equations:

$$S_1 = \frac{S_{in}}{(1 + k_1 X_1 V_1 t / V)} = \frac{S_{in}}{(1 + 0.1062t)} \quad (4.10)$$

$$S_2 = \frac{S_1}{(1 + k_2 X_2 V_2 t / V)} = \frac{S_1}{(1 + 0.0537t)} \quad (4.11)$$

$$S_3 = \frac{S_2}{(1 + k_3 X_3 V_3 t / V)} = \frac{S_2}{(1 + 0.0376t)} \quad (4.12)$$

$$S_4 = \frac{S_3}{(1 + k_4 X_4 V_4 t / V)} = \frac{S_3}{(1 + 0.0329t)} \quad (4.13)$$

$$S_5 = \frac{S_4}{(1 + k_5 X_5 V_5 t / V)} = \frac{S_4}{(1 + 0.2209t)} \quad (4.14)$$

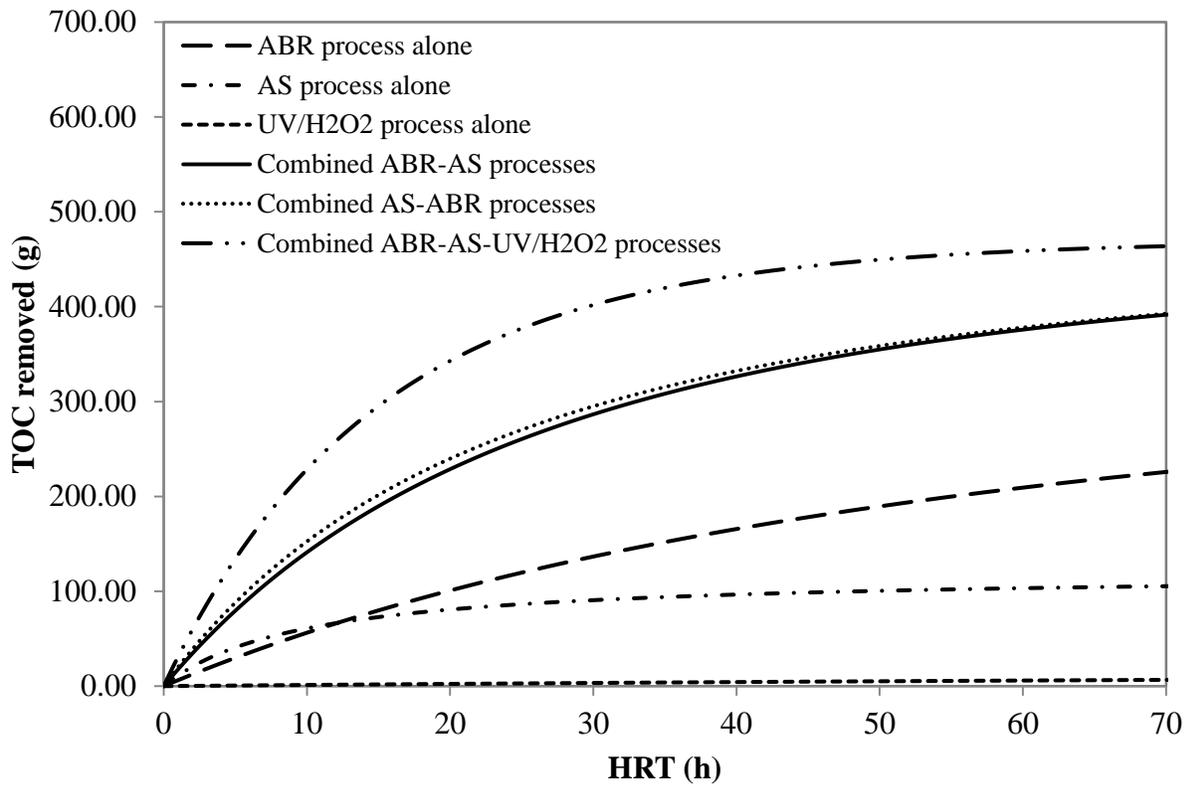


Figure 4.1. Mineralization of SWW in continuous mode without recycling for different processes.
 $TOC_{in} = 1000 \text{ mg/L}$. $Q = 5.90 \text{ mL/min}$.

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The coefficient in Equation (4.14) is increased compared to the ones in Equations (4.11) to (4.13). This might be due to the high value of k_5 in compartment 5. Since there is no recycling, $S_5 = S_f$, Equations (4.10) to (4.14) are reduced to Equations (4.15) and (4.16), which were used to predict the effluent TOC concentrations in the ABR, as part of combined processes and as an individual process, respectively.

$$S_f = \frac{S_{in}}{(1 + 9 \times 10^4 k_1 t / V)(1 + 8 \times 10^4 k_2 t / V)(1 + 1 \times 10^5 k_3 t / V)(1 + 7 \times 10^4 k_4 t / V)(1 + 8 \times 10^4 k_5 t / V)} \quad (4.15)$$

$$S_f = \frac{S_{in}}{(1 + 0.1062t)(1 + 0.0537t)(1 + 0.0376t)(1 + 0.0329t)(1 + 0.2209t)} \quad (4.16)$$

The non-linear least square function was used to determine the best-fit criterion, which means two sets of data are the closest to each other. The comparison between predicted values and the experimental data is presented in Figure 4.2a, which shows an agreement between the predicted model values and the experimental data. Therefore, Equation (4.16) could be used to predict the effluent TOC concentration at a specific HRT in the ABR process alone.

4.3.2. TOC degradation in AS

Equation (4.3) was used to calculate the first order rate constant in the AS reactor. Since there is no recycling, Equation (4.3) is reduced to Equations (4.17) and (4.18), which were used to predict the effluent TOC concentrations in the AS reactor, as part of combined processes and as an individual process, respectively.

$$S_f = \frac{S_{in}}{(1 + 2,399Kt)} \quad (4.17)$$

$$S_f = \frac{S_{in}}{(1 + 2.4669t)} \quad (4.18)$$

The comparison between predicted values and the experimental data is presented in Figure 4.2b, which shows an agreement between the predicted model values and the experimental data. Therefore, Equation (18) could be used to predict the effluent TOC concentration at a specific HRT in the AS process alone.

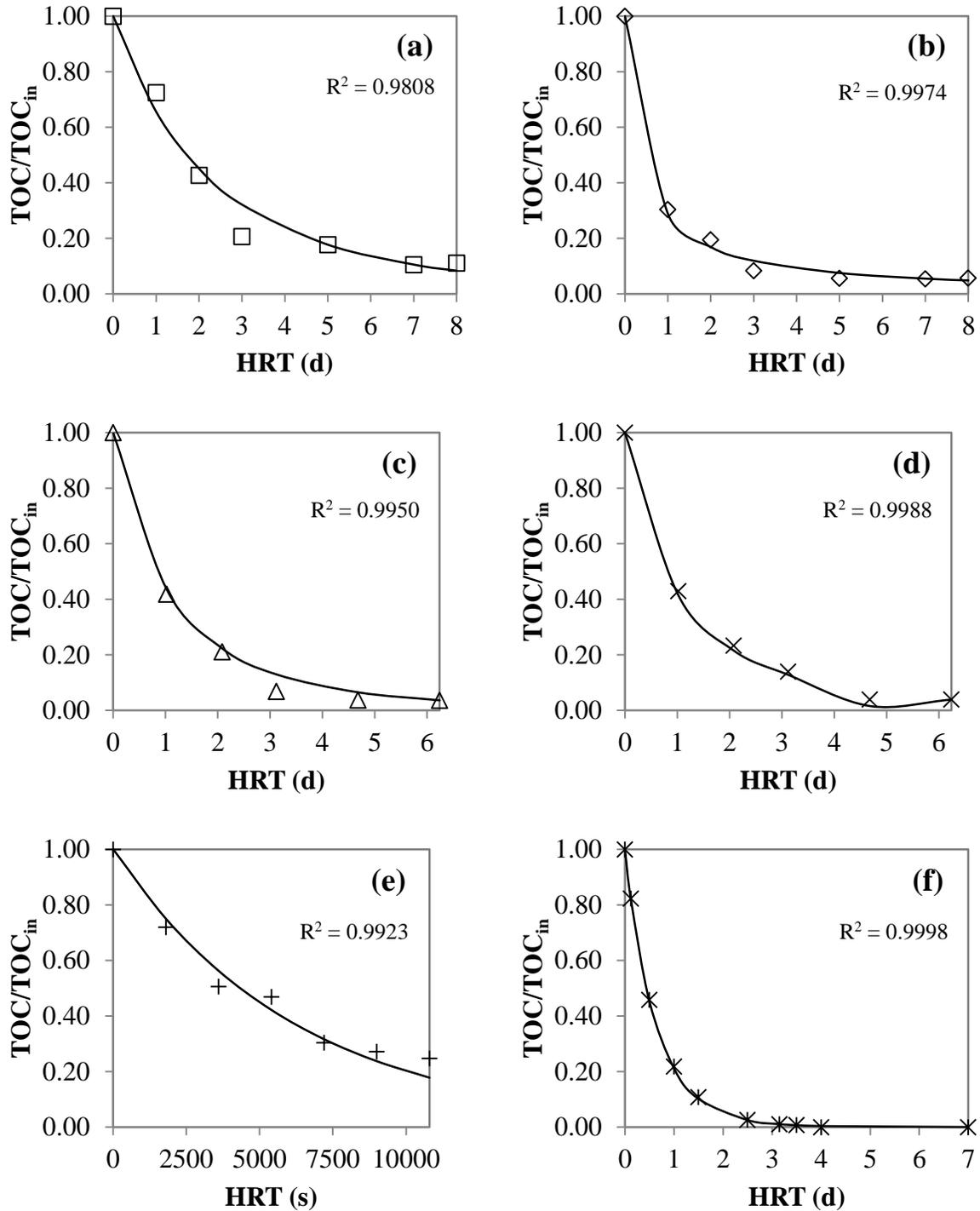


Figure 4.2. Comparison of the TOC/TOC_{in} predicted values using Equation (4.8) and the experimental data of the SWW treatment in continuous mode without recycling for different processes: (a) ABR, (b) AS, (c) ABR-AS, (d) AS-ABR, (e) UV/H₂O₂, and (f) ABR-AS-UV/H₂O₂. The markers are the corresponding experimental data. The lines are the corresponding model predictions. TOC_{in} = 1000 mg/L. Q = 5.90 mL/min.

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4.3.3. TOC Degradation in combined anaerobic-aerobic processes

For the combined biological processes, two equations were developed by combining Equations (4.15) and (4.17) as shown in Equations (4.19) and (4.20). To obtain Equation (4.19) for combined ABR-AS processes, Equation (4.15) is substituted in Equation (4.17) because the effluent of the ABR process is the influent of the AS process. Conversely, to obtain Equation (4.20) for combined AS-ABR processes, Equation (4.17) is substituted into Equation (4.15), because the effluent of the AS process is the influent of the ABR process. Therefore, Equations (4.19) and (4.20) were used to predict the effluent TOC concentrations in the combined ABR-AS processes and the combined AS-ABR processes, respectively.

$$S_f = \frac{S_{in}}{(1 + 0.1895t)(1 + 0.0269t)(1 + 0.0278t)(1 + 0.0168t)(1 + 0.1412t)(1 + 0.5505t)} \quad (4.19)$$

$$S_f = \frac{S_{in}}{(1 + 0.07974t)(1 + 0.0185t)(1 + 0.0021t)(1 + 0.0784t)(1 + 0.1053t)(1 + 0.0866t)} \quad (4.20)$$

The comparison between predicted values and the experimental data for combined ABR-AS and AS-ABR processes are presented in Figure 4.2c and d, respectively. These figures show an agreement between the predicted model values and the experimental data. Therefore, Equations (4.19) and (4.20) could be used to predict the effluent TOC concentrations at a specific HRT for combined ABR-AS and AS-ABR processes, respectively.

4.3.4. TOC Degradation in UV/H₂O₂ process

Equation (4.8) was used to predict the TOC degradation in the UV/H₂O₂ process alone due to a high concentration in the influent of up to 1000 mg TOC/L. Likewise, due to expected TOC concentrations of less than 100 mg/L after combined anaerobic-aerobic processes, Equation (4.9) was used to predict the TOC degradation in the UV/H₂O₂ process as post-treatment in combined processes. Thus, Equations (4.21) and (4.22) are obtained for individual and combined processes, respectively.

$$S_f = S_{in} \times \exp(-7.10 \times 10^{-8}t) \quad (4.21)$$

$$S_f = S_{in} \times \exp\left(\frac{-8.00 \times 10^{-6}t}{[H_2O_2]}\right) \quad (4.22)$$

The comparison between predicted values and the experimental data for the UV/H₂O₂ process alone is presented in Figure 4.2e. This figure shows an agreement between the predicted model values and the experimental data. Therefore, Equation (4.21) could be used to predict the effluent TOC concentration at a specific HRT for the treatment of SWW by UV/H₂O₂ process alone.

4.3.5. TOC degradation in combined anaerobic-aerobic and UV/H₂O₂ processes

For the combined ABR-AS-UV/H₂O₂ processes, Equations (4.15), (4.17) and (4.22) were combined. As a result, Equation (4.23) was used to predict the effluent concentrations of TOC for the combined ABR-AS and UV/H₂O₂ processes.

$$S_f = \frac{S_{in} \exp(-0.0393t/[H_2O_2])}{(1+0.3027t)(1+0.1341t)(1+0.0949t)(1+0.0465t)(1+0.0442t)(1+0.2201t)} \quad (4.23)$$

The comparison between predicted values and the experimental data for the combined ABR-AS-UV/H₂O₂ processes is presented in Figure 4.2f. This figure shows an agreement between the predicted model values and the experimental data. Therefore, Equation (4.23) could be used to predict the effluent TOC concentration at a specific HRT for the treatment of SWW using combined ABR-AS-UV/H₂O₂ processes.

4.3.6. Economic analysis

The cost of electricity per mass of TOC removed was estimated by Equation (4.1), which was defined for high TOC influent concentration, for each process by using the estimated values of the TOC concentrations in the influent (S_{in}) and effluent (S_f) obtained by Equations (4.16), (4.18) to (4.21), and (4.23) for the ABR, AS, combined ABR-AS, combined AS-ABR, UV/H₂O₂, and combined ABR-AS-UV/H₂O₂ processes, respectively.

Figure 4.3 shows the operational costs per kilogram of TOC removed, including optimization of HRT and H₂O₂ consumption for six processes as a function of the percentage of TOC removed. The UV/H₂O₂ alone is the least efficient technology with an optimum removal of 49.88% at a high cost of 67.06 \$/kg of TOC removed.

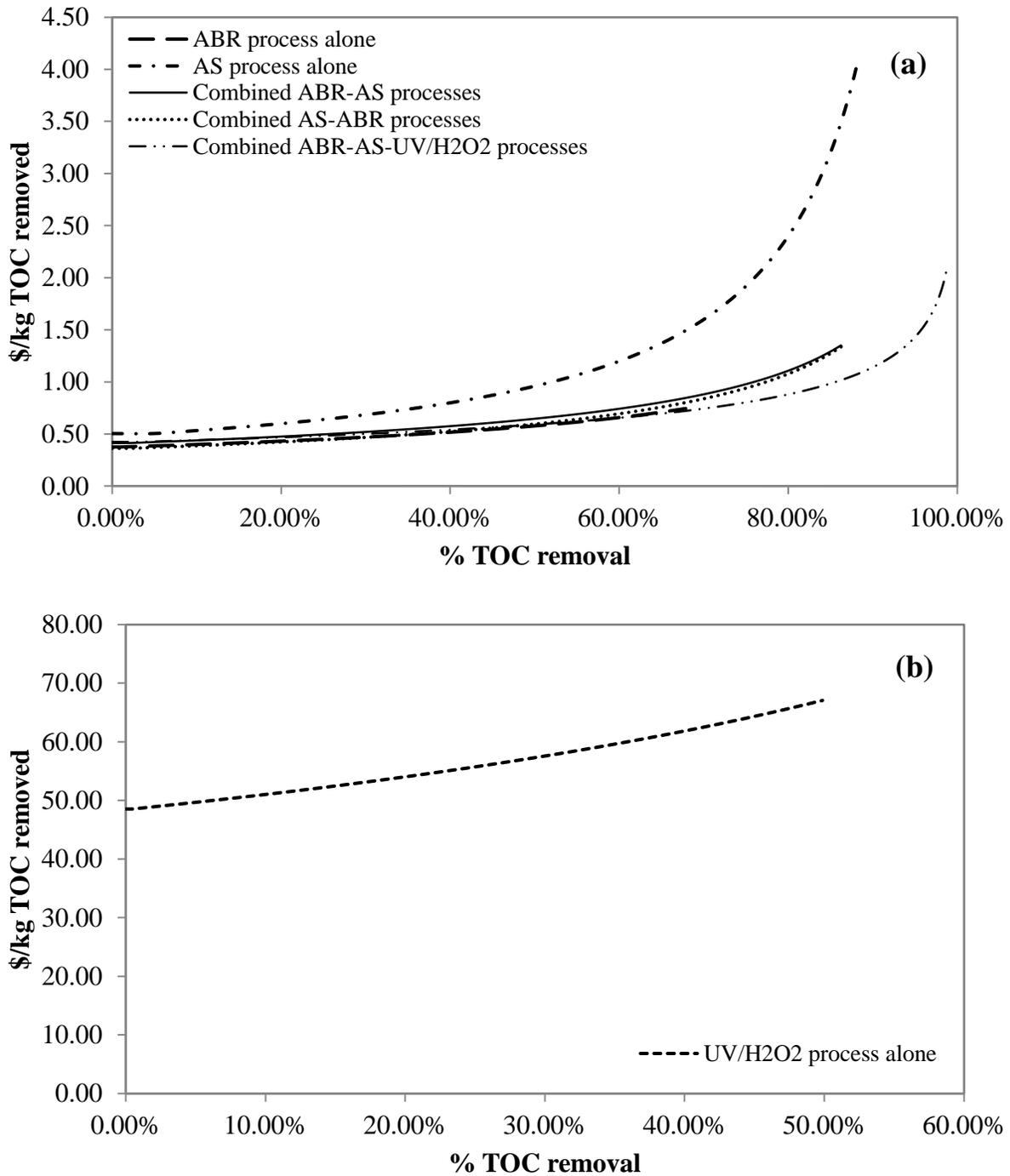


Figure 4.3. Operation costs per kilogram of TOC removed for each process: (a) ABR process alone, AS process alone, combined ABR-AS processes, combined AS-ABR processes, and ABR-AS-UV/H₂O₂ processes; (b) UV/H₂O₂ process alone, as a function of TOC removal in continuous mode without recycling. TOC_{in} = 1000 mg/L. Q = 5.90 mL/min.

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The TOC removal does not significantly increase by augmenting the HRT (Figure 4.3b). In contrast, it was observed that the AS is an efficient process with an optimum TOC removal of 88.10% at a cost of 4.03 \$/kg of TOC removed (Figure 4.3a).

The absolute operational costs (\$) compared to the percentage of TOC removed is shown in Figure 4.4. Two important facts should be noted, the costs increase with the amount of TOC removed for all six processes, especially when high TOC removal rates are achieved; and also, if low or intermediate amounts of TOC are to be removed, combined processes and individual processes are comparable in economic terms.

Finally, Figure 4.5 summarizes the operational costs for six processes in terms of \$/m³ of treated wastewater, which is a useful measurement from an industrial viewpoint. It is confirmed that costs (\$/m³) increase dramatically with the TOC removal because of the electricity consumption in the UV/H₂O₂ process alone, reaching values ten times higher than those of the processes that use biological treatment. Thus, in the combined processes, the main costs are initially for pumps, reagents, and air injection. However, when the removal rate of TOC is greater than 60%, the electricity costs gradually increase. Therefore, the technology to produce biogas can be added to traditional anaerobic wastewater treatment systems, which can be used as an on-site renewable source of energy (Siqueira et al., 2013). Thus, cost savings could be expected for MPPs because energy costs may be offset by the production of on-site power from anaerobic wastewater treatment (González-González et al., 2013).

4.4. Conclusions

A CEA was used to determine the best alternative for SWW treatment from six different systems evaluated in this economic study, including UV/H₂O₂, AS, ABR, ABR-AS, AS-ABR, and ABR-AS-UV/H₂O₂ processes. Thus, HRT was optimized since HRT affects the final removal efficiency of organic pollutants in wastewater and the operating costs of the system. The combined ABR-AS-UV/H₂O₂ processes were more technically efficient than other processes, removing 15% more TOC during the same amount of operating time. The UV/H₂O₂ process alone is the least efficient technology with an optimum removal of 49.88% at a high cost of 67.06 \$/kg of TOC removed. If low or intermediate amounts of TOC are to be removed, combined and individual processes are comparable in economic terms.

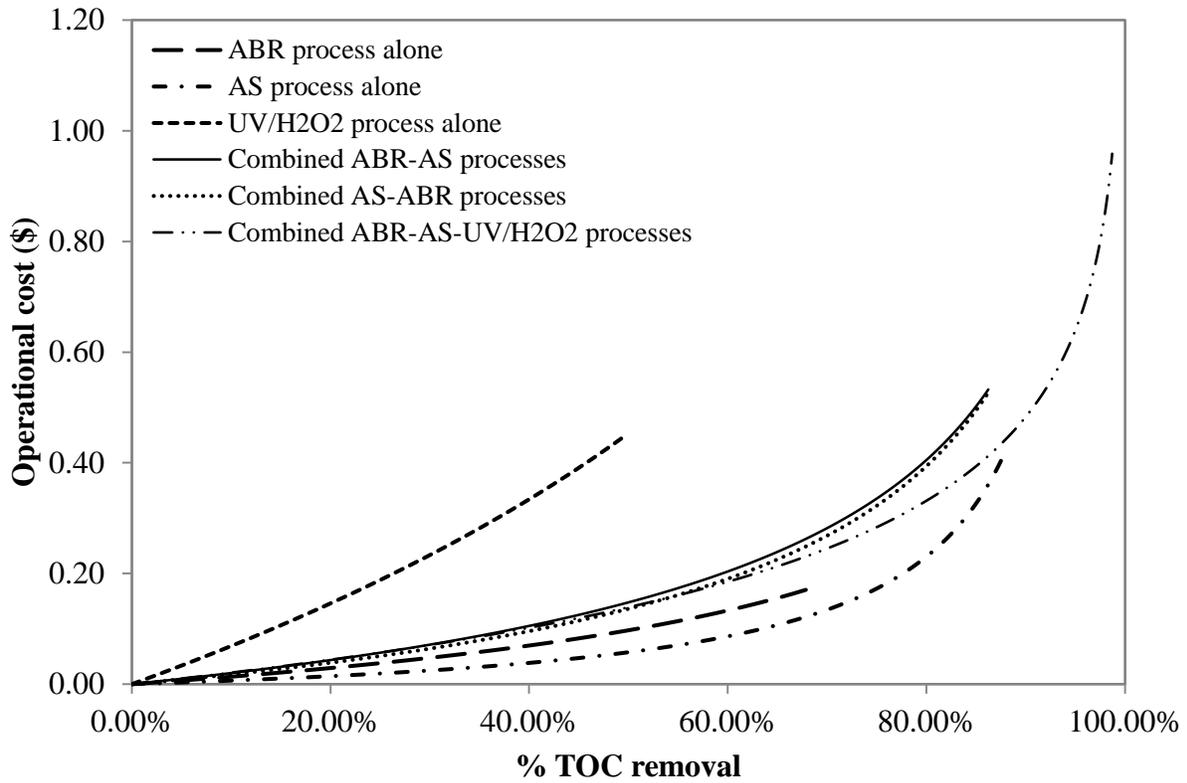


Figure 4.4. Absolute operation costs compared with percentage of TOC removal for different processes in continuous mode without recycling. $TOC_{in} = 1000$ mg/L. $Q = 5.90$ mL/min.

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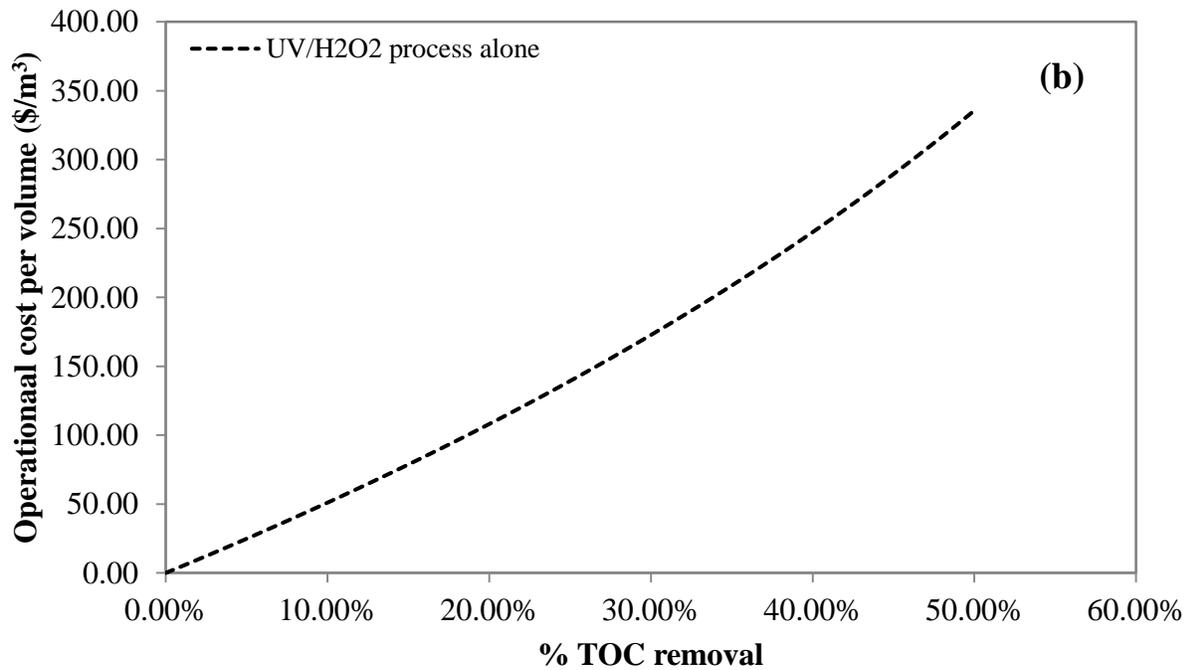
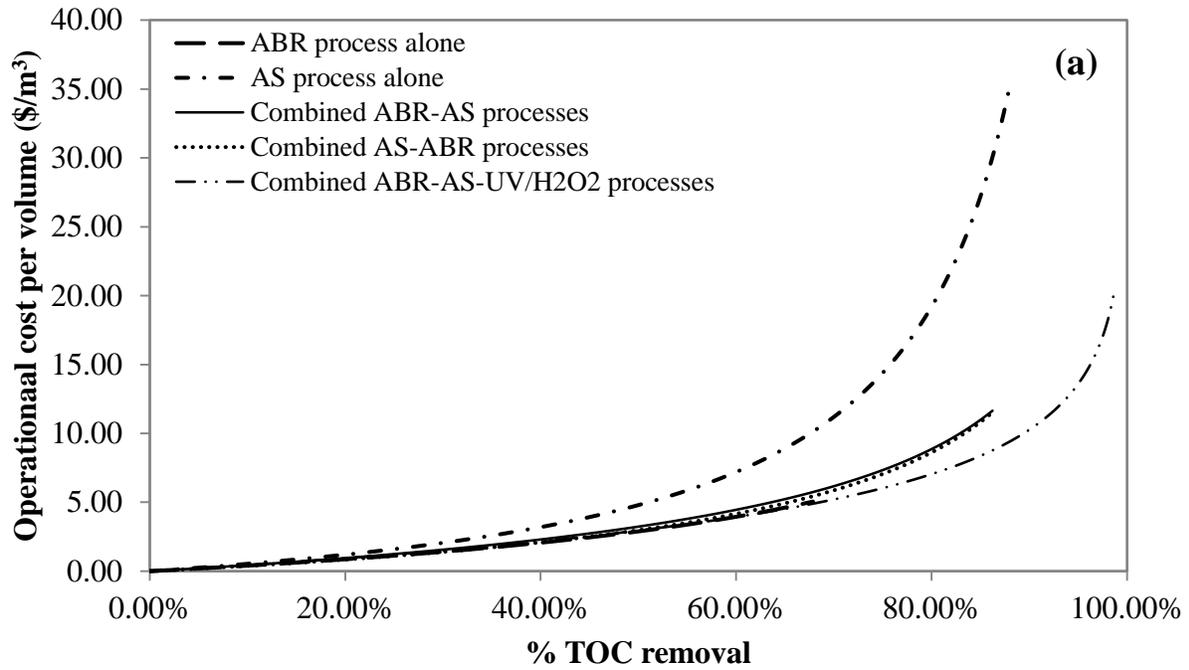


Figure 4.5. Operational costs per m³ of treated water compared with mineralization degree: comparison between the (a) ABR process alone, AS process alone, combined ABR-AS processes, combined AS-ABR processes, combined ABR-AS-UV/H₂O₂ processes, and (b) UV/H₂O₂ process alone in continuous mode without recycling. $TOC_o = 1000$ mg/L. $Q = 5.90$ mL/min.

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In combined processes, the main costs are initially for pumps, reagents, and air injection. Only when the TOC removal is higher than 60%, the electricity costs increase. Finally, it was determined that the optimum system for the TOC removal was ABR-AS-UV/H₂O₂, with an optimal TOC removal of 92.46% at an HRT of 41 h, at a cost of 1.25 \$/kg of TOC removed and \$11.60/m³ of treated SWW. It should be noted that this process reaches a TOC removal of 99% at a HRT of 76.5 h (3.19 days) with an estimated operational cost of 2.19 \$/kg of TOC removed and 21.65 \$/m³ of treated SWW, equivalent to 6.79 \$/(m³ day) that could be reduced by subtracting the electrical costs by considering potential energy recovery from anaerobic pre-treatment. The combined ABR-AS-UV/H₂O₂ system has been proven to be the most cost-effective solution among other processes for TOC removal. However, it may be necessary to assess its cost-effectiveness to all major constituents of SWW (i.e., BOD, COD, TN, etc.) in order to adopt such system for treating SWW.

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CHAPTER 5

TREATMENT OF ACTUAL SLAUGHTERHOUSE WASTEWATER BY COMBINED ANAEROBIC-AEROBIC PROCESSES FOR BIOGAS GENERATION AND REMOVAL OF ORGANICS AND NUTRIENTS: AN OPTIMIZATION STUDY TOWARDS A CLEANER PRODUCTION IN THE MEAT PROCESSING INDUSTRY*

Abstract

Environmental protection initiatives and the increasing market demands for green practices are driving the meat processing industry to consider sustainable methods for wastewater treatment since slaughterhouse wastewater (SWW) is seen as detrimental worldwide. Thus, on-site treatment is the preferred option to treat the slaughterhouse effluents for water reuse and potential energy recovery due to the conversion of organics into biogas. The treatment of an actual SWW is studied in a combined biological system. An anaerobic baffled reactor (ABR) followed by an aerobic activated sludge (AS) reactor are used in continuous mode at laboratory scale. Response surface methodology (RSM) is used for process optimization to maximize biogas yield and to remove the total organic carbon (TOC) and total nitrogen (TN) while minimizing the total suspended solids (TSS) residuals. The effects of the flow rate, pH, influent TOC concentration, and their interactions on the overall treatment efficiency and the biogas yield are studied. Maximum TOC and TN removals of 85.03 and 72.10%, minimum TSS residual of 19.54 mg/L, and maximum biogas yield of 116.56 mL/min are found at the optimum operating conditions of influent TOC concentration of 343 mg/L, feed flow rate of 63 mL/min, and pH of 6.84. The agreement between model predictions and experimental values indicates that the proposed model could describe the performance of combined anaerobic–aerobic systems for SWW treatment and the reduction of operating costs via biogas production while providing high-quality treated effluent for water reuse.

Keywords: Slaughterhouse wastewater, anaerobic digestion, activated sludge, combined processes, response surface methodology, biogas yield.

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C. Bustillo-Lecompte and M. Mehrvar (2016) Treatment of actual slaughterhouse wastewater by combined anaerobic-aerobic processes for biogas generation and removal of organics and nutrients: an optimization study towards a cleaner production in the meat processing industry. *Journal of Cleaner Production*. (Submitted).

5.1. Introduction

Generally, it is desirable to categorize and minimize wastewater generation at its source. Although typical water consumption varies considerably in the meat processing business, a regular slaughterhouse generates vast amounts of wastewater and is commonly a not efficient user of fresh water. Slaughterhouse wastewater (SWW) effluents are becoming one of the major agribusiness concerns worldwide because of the elevated amounts of water used during slaughtering, processing, and cleaning of the abattoir facilities.

Although physical, chemical, and biological treatment can be used for SWW degradation, each treatment process has different benefits and drawbacks depending on the SWW characteristics, best available technology, jurisdictions, and regulations. Furthermore, the recovery of valuable by-products from the slaughterhouse effluents is currently focused on high-quality treatment, biogas generation, nutrients, and fertilizers (Kist et al., 2009; Rajakumar et al., 2011; Barrera et al., 2012; Franke-Whittle and Insam, 2013; Bustillo-Lecompte et al., 2013, 2014, 2016a, 2016b; Bustillo-Lecompte and Mehrvar, 2015, 2016b).

The global production of meat, including beef, pork, and poultry, is projected to progressively grow until 2050. The number of slaughterhouses are augmenting, which represents an expected increase in the amount of SWW requiring treatment (Bustillo-Lecompte and Mehrvar, 2016b). SWWs are classified as one of the most detrimental industrial wastewaters by different agencies worldwide (Bustillo-Lecompte and Mehrvar, 2015) since the inadequate management of SWW is one of the reasons for rivers deoxygenation and groundwater pollution. Thus, the treatment and adequate disposal of SWW are a global economic and public health necessity and these effluents require significant treatment for a safe and sustainable release to the environment and (Bustillo-Lecompte et al., 2016b).

Anaerobic processes appear to be economically more attractive than aerobic processes for the treatment of SWW by achieving low sludge production and low energy requirement. However, anaerobically treated effluents should be further treated by other treatment methods to fulfill the discharge requirements (Chan et al., 2009; Bustillo-Lecompte et al., 2013). Therefore, combined anaerobic-aerobic processes could lead to a reduction in operation and maintenance costs, which make them more attractive than conventional methods (Tabrizi and Mehrvar, 2004; Mehrvar and Tabrizi, 2006; Bustillo-Lecompte et al., 2014). Other advantages include high removal efficiencies, smaller

amounts of aerobic sludge production, and potential energy recovery due to the conversion of organics into biogas (Chan et al., 2009; Bustillo-Lecompte and Mehrvar, 2015).

The SWW treatment is usually evaluated in terms of bulk parameters due to the variation of the SWW characteristics related to the type of animals slaughtered. Typical parametrical analyses include pH, chemical oxygen demand (COD), biochemical oxygen demand (BOD), total nitrogen (TN), total organic carbon (TOC), and total suspended solids (TSS) (Cao and Mehrvar, 2011; Barrera et al., 2012; Bustillo-Lecompte et al., 2013, 2014, Bustillo-Lecompte and Mehrvar, 2015). Hence, the interaction of cross-factor and single-factor effects on the overall process efficiency and biogas yield has not been widely evaluated, rather the microorganism characterization, disinfection, and denitrification are the main focus in recent years (Franke-Whittle and Insam, 2013; Bustillo-Lecompte and Mehrvar, 2015).

Consequently, the design of experiments (DOE) is used to surpass the limitations of traditional experimental methods in terms of time, materials, and the number of experimental trials. Likewise, the DOE permits the optimization of all parameters and consider the combined effects of all the factors involved. Besides, the response surface methodology (RSM) is used for cross-factor interaction analysis to achieve optimal responses using the minimum number of experiments (Ghafoori et al., 2012, 2014, 2015; Bustillo-Lecompte et al., 2016; Šereš et al., 2016).

In this study, the effects of the flow rate, pH, the influent concentration of TOC, and their interactions on the overall efficiency of the combined anaerobic-aerobic processes and the biogas yield for the SWW treatment were investigated. The DOE was used to optimize the SWW treatment using combined anaerobic baffled reactor (ABR) and aerobic activated sludge (AS) reactor in continuous mode at the laboratory scale by maximizing the biogas yield and the removal of TOC and TN while minimizing the TSS concentration in the effluent.

The optimal parametric values for the DOE were obtained using a Box–Behnken design (BBD) with three factors at three levels combined with RSM. Statistical models were also developed to predict the percent TOC and TN removal, the effluent concentration of TSS, and biogas yield as response variables by the combined anaerobic–aerobic processes. The statistical models were validated by an additional set of experiments at the optimum conditions in line with the DOE results. The use of combined biological processes as an alternative to conventional methods is a cost-effective approach for the treatment of meat processing effluents and adherence to pertinent regulations worldwide. As a

result, the proposed models on SWW treatment by the combined ABR–AS system could be used as a base for future studies for the reduction of operating costs while providing high-quality treated effluents for water reuse.

5.2. Materials and methods

5.2.1. Materials

Actual SWW samples, with an average TOC concentration of 862 mg/L, were taken from selected provincially licensed meat processing plants directly from their source in Ontario, Canada (OMAFRA, 2015b). The overall SWW characteristics from the selected meat processing plants are shown in Table 5.1.

Table 5.1. Characteristics of the actual slaughterhouse wastewater from selected provincially licensed meat processing plants.

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Parameter	Range
BOD (mg/L)	37.95-1,339
COD (mg/L)	87.23-2,080
TN (mg/L)	161.2-254.7
TOC (mg/L)	90.41-1,694
TP (mg/L)	0.257-22.98
TSS (mg/L)	0.390-103.5
pH	6.8-7.0

5.2.2. Experimental setup and procedure

A combined ABR–AS continuous system at the laboratory scale was used for the treatment of actual SWW. Figure 1 illustrates the schematic diagram of the experimental setup for the combined ABR–AS processes. The 50 L combined ABR–AS system consisted of a 36-L ABR with five equal-volume chambers integrated with individual headspaces, biogas collection piping, and a 14-L aerobic AS reactor with a monitored air flow rate. A 45° slanted-edge baffle within each ABR chamber permits the downflow and upflow course of the SWW, providing effective mixing and contact time between the SWW and the biomass. The AS air flow rate was set at 2 L/min to guarantee nitrifying bacteria growth and dissolved oxygen (DO) concentrations over 2.0 mg/L.

5.2.2.1. Acclimatization of the inoculum

Twelve liters of an anaerobic sludge seed (38,000 mg/L), using 2.4 L of the inoculum for each of the five chambers of the ABR (1/3 of the total working volume), and 5 L of an aerobic sludge seed (3,000 mg/L) were loaded into the anaerobic and aerobic bioreactors, respectively. The inoculum was acclimatized in eight weeks by feeding the actual SWW continuously into the bioreactors using a peristaltic pump at a constant flow rate of 75 mL/min.

During the 60-days acclimatization period, the influent substrate concentration was gradually increased biweekly from 25, 50, and 75% to 100% of the actual SWW. Biomass growth within the combined ABR–AS processes was monitored by collecting samples from each compartment of both ABR and AS bioreactors during the acclimatization period by measuring the concentrations of both total suspended solids (TSS) and volatile suspended solids (VSS).

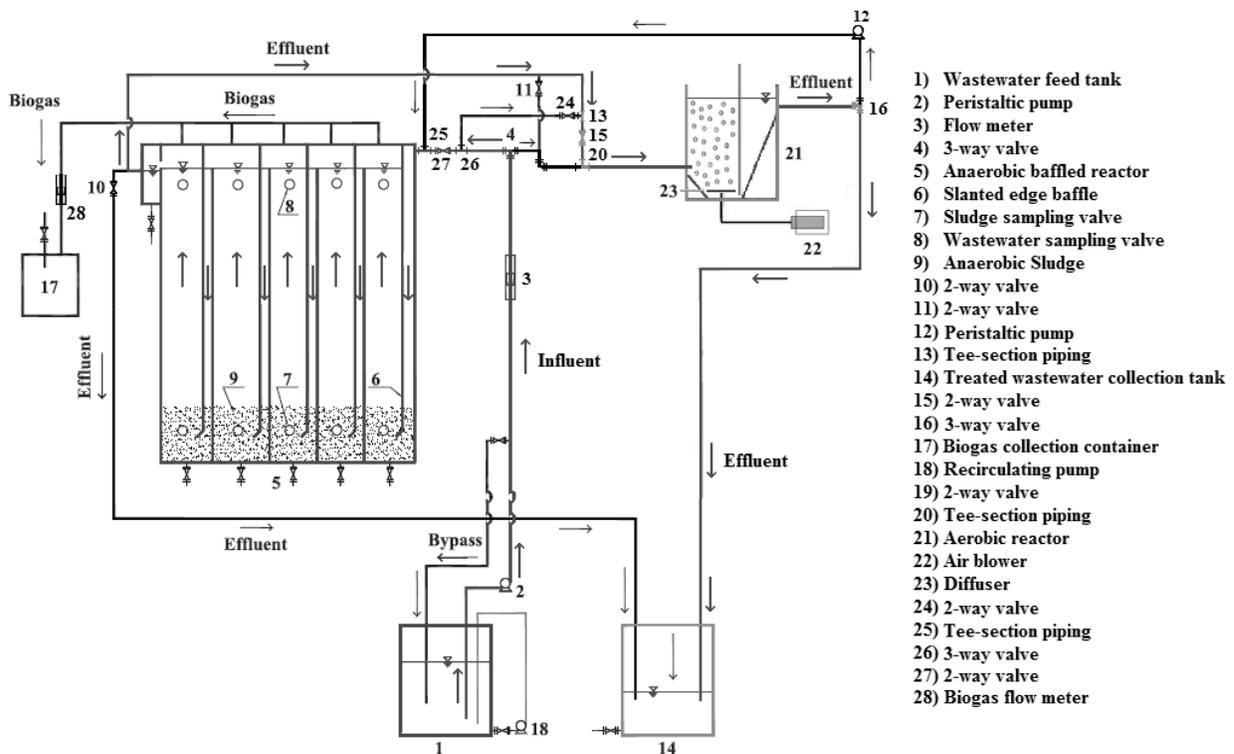


Figure 5.1. Schematic diagram of the combined anaerobic-aerobic processes for the treatment of SWW.

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5.2.2.2. Slaughterhouse wastewater treatment and sample analysis

After the 8-week acclimatization period, the following procedure was used in performing each experiment in the combined ABR–AS processes for quality control:

- 1) SWW samples were filtered to separate the liquid portion of the wastewater from the solids.
- 2) Filtered SWW samples were then diluted to reach the desired TOC concentration of the feed in a 120-L solution.
- 3) A 1 N solution of sulfuric acid (H_2SO_4) and a 50% solution of sodium hydroxide (NaOH) were used to adjust the pH.
- 4) The SWW solution with the desired TOC concentration and pH was fed into the combined ABR–AS processes by a variable speed peristaltic pump to control and adjust the flow rate.
- 5) Effluent samples were taken at 3 h intervals until the system reached steady state conditions.

TOC and TN concentrations were analyzed for each sample using an automated TOC/TN analyzer (Teledyne Tekmar Apollo 9000, Mason, OH). DO, pH, and temperature were measured daily using a dissolved oxygen meter (YSI 58 Dissolved Oxygen Meter, Yellow Springs, OH) and a pH meter (Thermo Scientific Orion 230A+, Ottawa, ON), respectively. The concentrations of TSS and VSS were measured according to the American Public Health Association (APHA, 2012) standards methods. The colorimetric method (Orbeco-Hellige MC500 Multi-Parameter Colorimeter, Sarasota, FL) was used for routine analysis of COD, TP, and Turbidity (APHA, 2012).

Moreover, the biodegradability of the SWW and the 5-days biochemical oxygen demand (BOD_5) were examined via respirometry assays. Four 1-L respirometry bioreactors (Bioscience BI-2000 Electrolytic, Allentown, PA) were inoculated using AS with an initial biomass concentration of 1,000 mgVSS/L.

The respirometry bioreactors were then filled with samples of SWW, treated SWW by ABR alone, treated SWW by aerobic AS bioreactor alone, and treated SWW by combined ABR–AS processes. Biogas analysis was performed using a portable gas analyzer (Landtec Biogas 5000, Colton, CA) for CH_4 , CO_2 , and O_2 volume percentage measurement. All experiments were repeated in triplicates; thus, average values were reported.

5.2.2.3. Experimental design and optimization

A three-factor along with three-level BBD in conjunction with RSM was used to maximize the biogas yield and the removal of TOC and TN while minimizing the TSS residuals. The influent concentration of TOC (X_1), flow rate (X_2), and pH (X_3) were used as independent factors in the DOE. The percent TOC and TN removals, the TSS residual, and the biogas yield were considered as the process responses. Thus, each factor was coded at three levels (-1, 0, +1) as shown in Table 5.2. Preliminary experiments were used to determine and select the particular ranges of the factors.

Table 5.2. Independent variables with coded levels based on a three-factor, three-level BBD.

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Independent variable	Symbol	Coded levels		
		-1	0	1
TOC _{in} (mg/L)	X_1	100	850	1,600
Flow rate (mL/min)	X_2	45	75	105
pH	X_3	5	7	9

A quadratic model was used to estimate the parametric coefficients by correlating dependent and independent variables using the least-squares regression as shown in Equation (1) (Ghafoori et al., 2012, 2014, 2015; Bustillo-Lecompte et al., 2016a, 2016b; Bustillo-Lecompte and Mehrvar, 2016b):

$$Y_i = \beta_o + \sum_{i=1}^k \beta_i X_i + \sum_{i=1}^k \beta_{ii} X_i^2 + \sum_{i=1}^{k-1} \sum_{j=2}^k \beta_{ij} X_i X_j + c \quad (5.1)$$

where β_o , β_i , β_{ii} , and β_{ij} are the constant, linear, quadratic, and cross-factor interaction coefficients, respectively; X_i and X_j represent the independent variables; Y_i is the predicted response; and k and c are the number of factors and the residual term, respectively.

The statistical software Design-Expert 9.0.4.1 was employed for the DOE and the estimation of the coefficients for each response function. The significance of each model equation, individual parameters, and factor interactions were evaluated by analysis of variance (ANOVA) at the confidence intervals of 95% ($\alpha = 0.05$).

Two-dimensional (2D) contour plots and three-dimensional (3D) surface responses were obtained in the quadratic models. Additional experimental runs were carried out to validate the quadratic models for maximum biogas yield, percent removals of TOC and TN, and minimum TSS in the effluent at the optimal operating conditions, calculated by the software numerical optimization method.

On the other hand, to obtain a simultaneous objective function that represents the geometric mean of all transformed responses, the desirability multiple response method was used to combine the desirable ranges for each response as shown in Equation (5.2) (Myers et al., 2009):

$$D = (d_1 \times d_2 \times d_3 \times d_4 \dots \times d_n)^{1/n} = \left(\prod_{i=1}^n d_i \right)^{1/n} \quad (5.2)$$

where D , d_i , and n are the desirability objective function, each individual response range, and the number of responses, respectively. For a simultaneous optimization, each response requires low and high values for the optimization. Otherwise, if any response is found outside of its desirability range, the overall desirability becomes equal to zero. In this case, the percent removal of TOC (d_1), TN (d_2), and biogas yield (d_3) are maximized while the TSS residual (d_4) is minimized.

5.3. Results and discussion

5.3.1. Acclimatization period

TSS and VSS concentrations were measured in both AS bioreactor and ABR, respectively, to observe the growth of the microorganisms while they were adapting to the bioreactor and SWW conditions. The SWW concentration was gradually increased to the highest TOC value (1,718 mg/L) of the SWW samples.

Figure 5.2 depicts a gradual growth in the biomass for the ABR and the AS bioreactor until the TSS and VSS were stabilized. After the 60-day acclimatization period, the anaerobic and aerobic biomass concentrations (VSS) increased to 24,000 and 2,800 mg/L, respectively. The temperature of the processes remained under sub-mesophilic conditions with an average temperature of 24.75°C in the combined ABR–AS system.

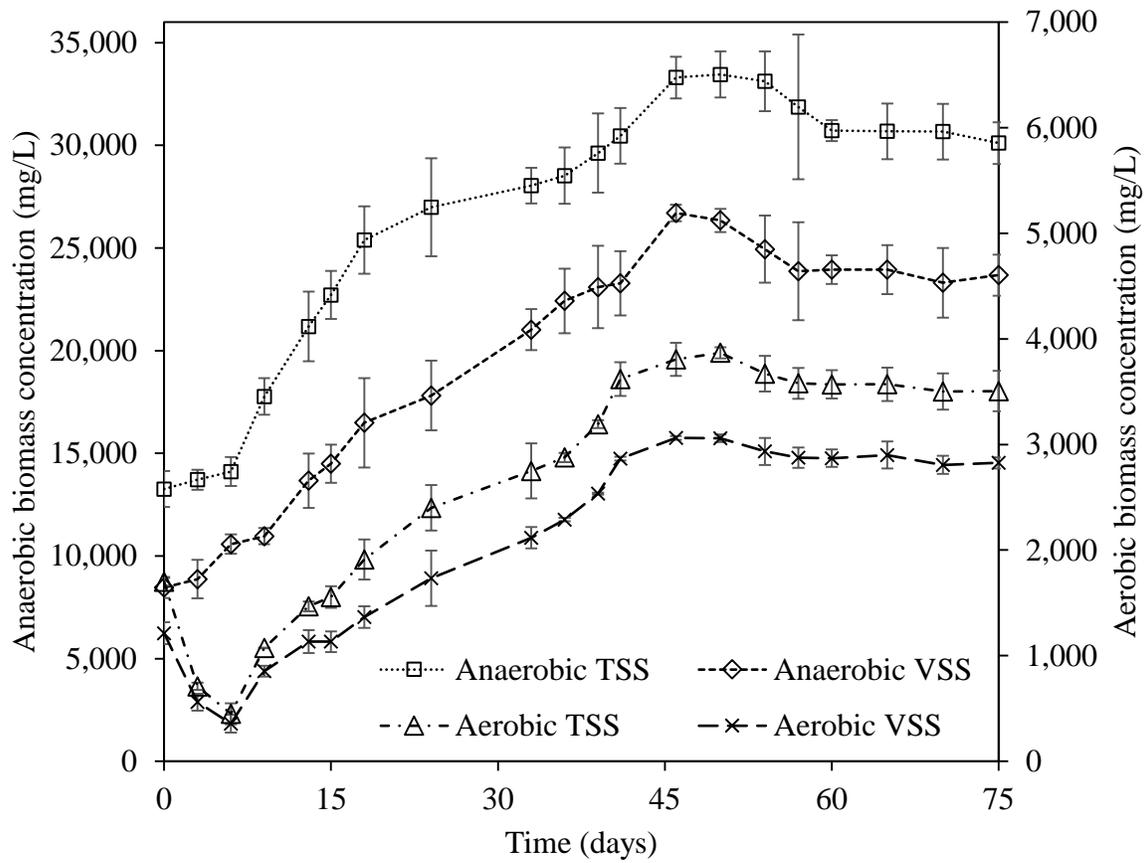


Figure 5.2. Biomass concentration in the anaerobic baffled reactor during acclimatization and the aerobic activated sludge bioreactor. Error bars represent the standard deviation of the experimental data.

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5.3.2. Preliminary experiments

Preliminary experiments were conducted for the treatment of SWW using the combined ABR–AS system. Bulk parameters including TOC, TN, COD, TSS, total phosphorus (TP), and turbidity were analyzed. Figure 5.3 shows the obtained maximum removal values for TOC (Figure 5.3a), TN (Figure 5.3b), COD (Figure 5.3c), TP (Figure 5.3d), turbidity (Figure 5.3e), and TSS (Figure 5.3f) from the SWW by the combined anaerobic-aerobic processes in continuous mode.

Furthermore, removal rates of up to 90, 81, 98, 84, 97, and 95% were obtained for TOC, TN, COD, TP, turbidity, and TSS, respectively. Influent concentrations of TOC, TN, COD, TP, and TSS of up to 941, 214, 1950, 0.38, and 750 mg/L, respectively, as well as an influent turbidity of 1,000 formazin turbidity units (FTU) were continuously fed to the combined ABR–AS system at a flow rate of 75 mL/min.

Respirometry assays were performed to evaluate the biodegradability of the SWW and the BOD removal efficiency of the individual and combined biological processes. Samples of raw SWW, treated SWW by ABR alone, treated SWW by aerobic AS reactor alone, and treated SWW by combined ABR–AS processes were evaluated as shown in Figure 5.4. The initial TOC concentration was set at 75.00 mg/L due to the small volume of the respirometry bioreactors (1 L). The theoretical oxygen demand was calculated to be 200.25 mg/L, similar to the measured ultimate oxygen uptake of 202.29 mg/L and the measured COD of 205.64 ± 6.43 mg/L.

Besides, the BOD₅ was obtained as the oxygen uptake at the 120 h mark for each sample. Therefore, the BOD₅ concentration of the raw SWW was found to be 147.96 mg/L, the BOD₅/COD ratio was 0.72, and the initial food to microorganism ratio (F/M) was calculated to be 0.46 mgO₂/mgVSS.day, which indicates a desirable F/M . As a result, the majority of the organics in the actual SWW are considered biodegradable (Bustillo-Lecompte et al., 2015). Figure 5.4 also illustrates the BOD₅ concentrations in the treated effluents by ABR alone, aerobic AS reactor alone, and combined ABR–AS processes to be 61.66, 47.75, and 23.72 mg/L, respectively. Thus, the BOD₅/COD ratios of 0.30, 0.23, and 0.11 for the treated effluents by ABR alone, aerobic AS reactor alone, and combined ABR–AS processes, respectively. It can be observed that as the SWW is oxidized, the BOD₅/COD ratio decreases. The SWW treated effluent becomes less biodegradable since it has already been largely degraded.

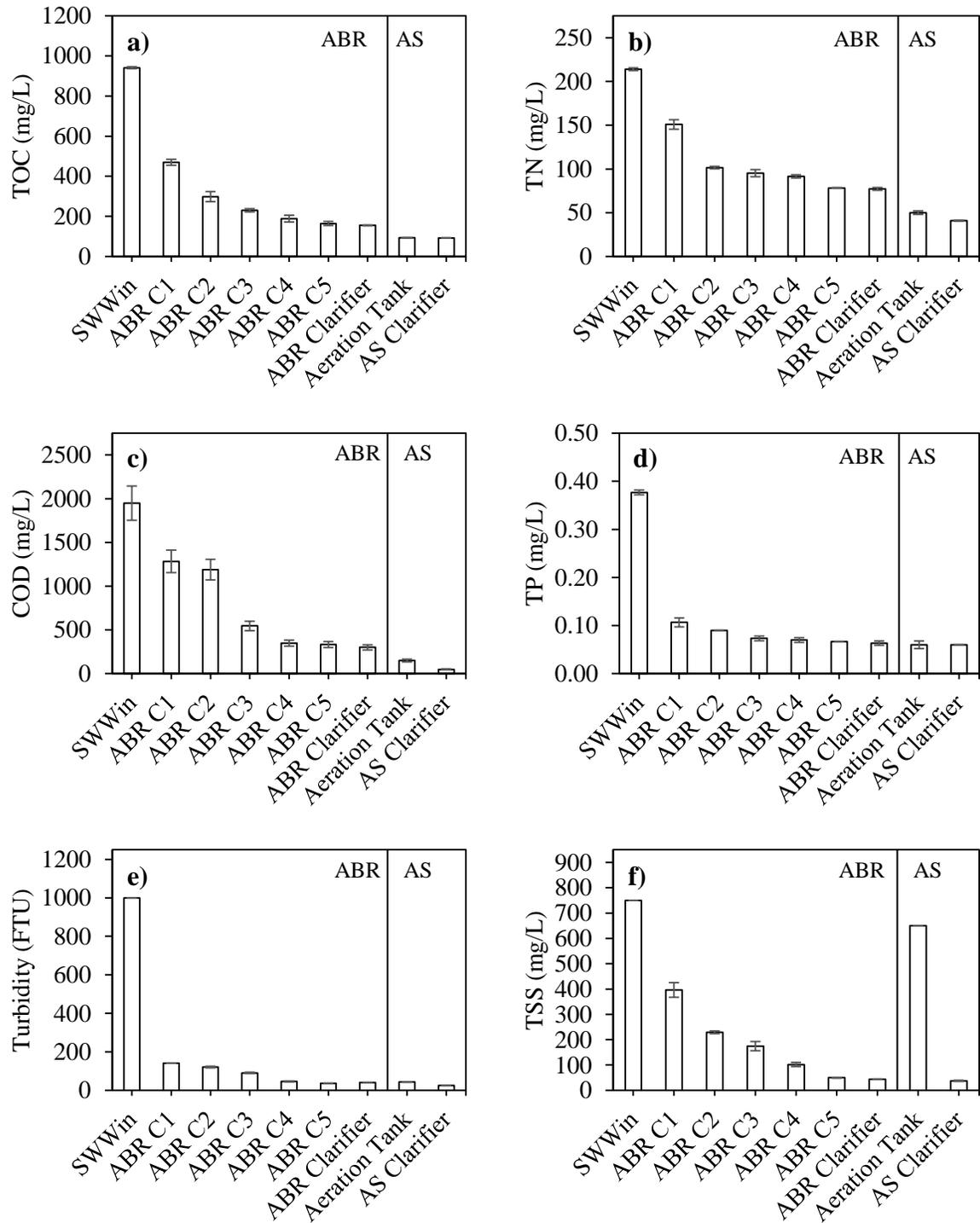


Figure 5.3. Maximum remaining values of (a) TOC, (b) TN, (c) COD, (d) TP, (e) Turbidity, and (f) TSS from SWW using combined anaerobic-aerobic processes in continuous mode with inlet concentrations of TOC, TN, COD, TP, and TSS of up to 941, 214, 1950, 0.38, and 750 mg/L, respectively, as well as an influent turbidity of 1000 formazin turbidity units (FTU). Error bars represent the standard deviation of the experimental data.

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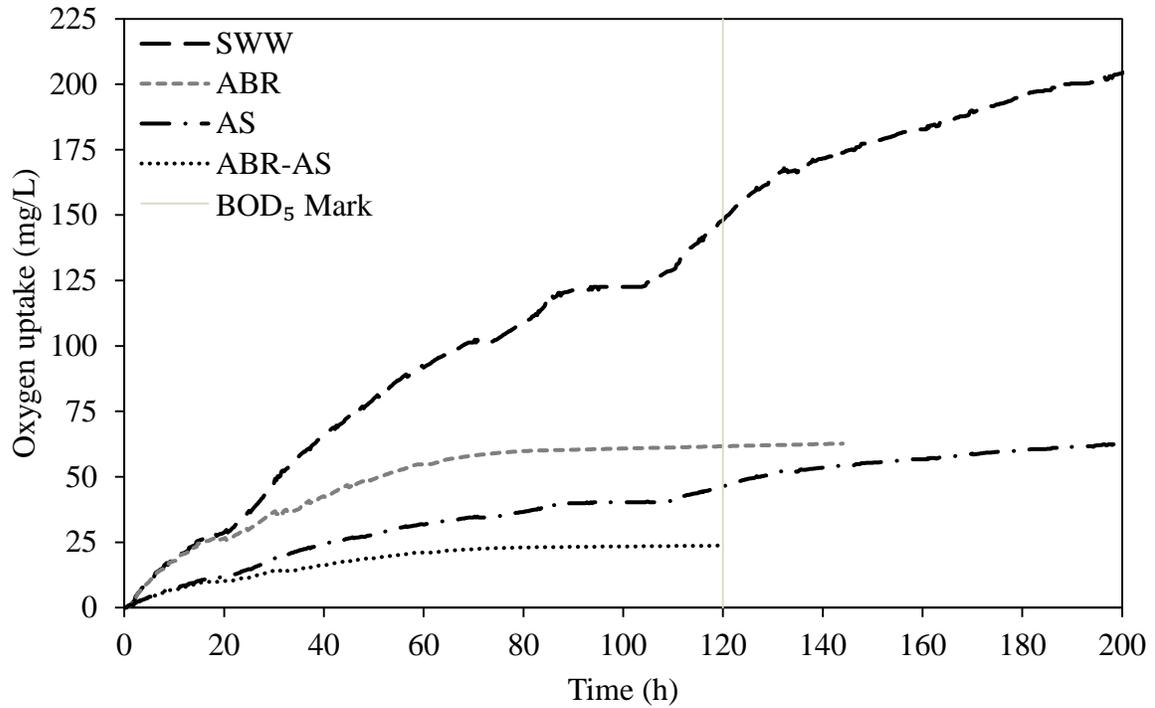


Figure 5.4. Respirometry testing results for different samples of raw SWW, treated SWW by aerobic AS bioreactor alone, treated SWW by ABR alone, and treated SWW by combined ABR–AS processes. The initial TOC concentration is 75.00 mg/L and mean standard deviation is 6.43 mg/L. BOD₅ is obtained as the oxygen uptake at the 120 h mark.

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5.3.3. Experimental design and statistical analysis

The influent TOC concentration was selected as one of the factors to be evaluated by DOE since the TOC analysis provides a more accurate appraisal of the total organic compounds present in a wastewater sample in comparison to BOD or COD, without producing any toxic analytical waste (Dubber and Gray, 2010; Bustillo-Lecompte et al., 2014, 2015). For nutrients evaluation, TN was selected due to the high concentration of TN in the influent SWW compared to that of TP. Furthermore, TN analysis was performed using an automated TOC/TN analyzer, which allowed rapid and accurate results while avoiding the generation of noxious analytical by-products compared to the vanadomolybdophosphoric acid colorimetric method used in TP analysis. The flow rate and the pH were also selected due to their direct relationship to microorganism activity and growth (Chan et al., 2009; Cao and Mehrvar, 2011; Bustillo-Lecompte et al., 2013).

Table 5.3 shows the three-factor, three-level BBD with observed and predicted values for the TOC and TN removal, the biogas yield, and the TSS residual of the combined ABR–AS continuous system. The RSM was used for parameter estimation, specifying the correlation between the input factors and the output responses, as previously shown in Equation (5.1). Consequently, in order to estimate the response functions for the percent TOC removal (Y_1), the percent TN removal (Y_2), the biogas yield (Y_3), and the TSS residual (Y_4), the second-order polynomial Equations (5.3) to (5.6) were developed in terms of the coded factors, including influent concentration of the TOC (X_1), the flow rate (X_2), and the pH (X_3):

$$Y_1 = 80.42 - 5.65X_1 - 2.49X_2 + 0.59X_3 + 3.13X_1X_2 - 1.29X_1X_3 + 2.69X_2X_3 - 1.55X_1^2 - 1.94X_2^2 - 3.00X_3^2 \quad (5.3)$$

$$Y_2 = 62.85 - 8.59X_1 - 9.29X_2 - 1.18X_3 + 7.43X_1X_2 + 6.48X_1X_3 + 0.35X_2X_3 - 4.86X_1^2 - 3.03X_2^2 - 18.84X_3^2 \quad (5.4)$$

$$Y_3 = 127.19 + 8.28X_1 - 1.40X_2 - 5.60X_3 - 8.51X_1X_2 - 6.77X_1X_3 + 2.57X_2X_3 - 0.35X_1^2 - 19.18X_2^2 - 12.84X_3^2 \quad (5.5)$$

$$Y_4 = 22.52 + 3.30X_1 + 5.03X_2 + 2.35X_3 + 2.60X_1X_2 + 1.52X_1X_3 + 0.64X_2X_3 + 1.58X_1^2 - 0.61X_2^2 + 6.37X_3^2 \quad (5.6)$$

Table 5.3. Three-factor, three-level BBD for RSM, along with the observed and predicted percent TOC removal, TN removal, Biogas yield, and TSS residual.

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Run	Independent coded variables			TOC removal (%)		TN removal (%)		Biogas yield (mL/min)		TSS residual (mg/L)	
	X ₁	X ₂	X ₃	Observed	Predicted	Observed	Predicted	Observed	Predicted	Observed	Predicted
1	-1	-1	0	88.87	88.19	79.53	80.28	94.02	92.26	18.62	17.74
2	1	-1	0	70.80	70.64	48.89	48.23	125.62	125.84	25.95	26.16
3	-1	1	0	76.81	76.97	46.17	46.83	106.70	106.48	29.83	29.62
4	1	1	0	71.25	71.93	45.25	44.50	104.28	106.04	33.43	34.31
5	-1	0	-1	79.03	79.65	56.92	55.41	103.24	104.55	33.14	33.36
6	1	0	-1	70.84	70.93	25.36	25.25	135.32	134.65	37.76	36.88
7	-1	0	1	83.49	83.40	39.98	40.09	106.22	106.89	34.15	35.03
8	1	0	1	70.15	69.53	34.35	35.86	111.22	109.91	44.83	44.61
9	0	-1	-1	80.01	80.07	51.04	51.81	104.28	104.73	27.90	28.57
10	0	1	-1	70.49	69.72	31.67	32.52	97.89	96.80	37.31	37.30
11	0	-1	1	75.09	75.86	49.60	48.75	87.30	88.39	31.98	31.99
12	0	1	1	76.34	76.28	31.64	30.87	91.18	90.73	43.95	43.28
13	0	0	0	80.83	80.42	61.67	62.85	127.25	127.19	29.52	29.52
14	0	0	0	79.94	80.42	62.27	62.85	125.13	127.19	28.71	29.52
15	0	0	0	80.45	80.42	62.81	62.85	126.13	127.19	29.10	29.52
16	0	0	0	81.05	80.42	63.45	62.85	129.01	127.19	29.92	29.52
17	0	0	0	79.83	80.42	64.05	62.85	128.41	127.19	30.35	29.52

Unfavorable effects are indicated by negative coefficients of the model components. In the case of TOC removal (Y_1), the unfavorable effects come from the model components X_1 , X_2 , X_1X_3 , X_1^2 , X_2^2 , and X_3^2 . Similarly, X_1 , X_2 , X_3 , X_1^2 , X_2^2 , and X_3^2 have unfavorable effects on the TN removal (Y_2). Correspondingly, X_2 , X_3 , X_1X_2 , X_1X_3 , X_1^2 , X_2^2 , and X_3^2 have unfavorable effects on the biogas yield (Y_3). In contrast, only X_2^2 was found to have an unfavorable effect on the TSS residual (Y_4). On the other hand, positive coefficients indicate favorable effects on the model responses. For the percent TOC removal (Y_1), the favorable effects come from the model components X_3 , X_1X_2 , and X_2X_3 . In the same way, the model components X_1X_2 , X_1X_3 , and X_2X_3 have favorable effects on the TN removal (Y_2). Likewise, X_1 and X_2X_3 have favorable effects on the biogas yield (Y_3). Finally, X_1 , X_2 , X_3 , X_1X_2 , X_1X_3 , X_2X_3 , X_1^2 , and X_3^2 are favorable to the TSS residual (Y_4).

ANOVA was employed with a 95% confidence interval to estimate the statistical significance of the four quadratic models for percent TOC removal (Y_1), TN removal (Y_2), biogas yield (Y_3), and TSS residual (Y_4). Consequently, each factor coefficient was evaluated in terms of statistical significance using the Fisher's (F) exact test by comparing probability (p) values greater than F . Thus, small probability values ($p < 0.05$) indicate the significance of the model parameters, whereas p -values > 0.10 indicate the non-significance of the model factors. The non-significance of the quadratic effect indicate the optimal levels are located at the limits of the experimental region (Botha et al., 2012; Bustillo-Lecompte et al., 2016a). As shown in Table 5.4, the developed quadratic models for each response were found to be significant. F -values of 85.84, 207.34, 122.09, and 77.16 were obtained for the percent TOC removal (Y_1), the percent TN removal (Y_2), the biogas yield (Y_3), and the TSS residual (Y_4), respectively.

Furthermore, the accuracy of the developed models to predict the response functions was confirmed by small probability values ($p < 0.05$). However, some model terms were found not to be significant ($p > 0.10$), including X_2X_3 for the percent TN removal; X_1^2 for the biogas yield; and X_2X_3 and X_1^2 for TSS residual. Besides, the adequate precision of the percent TOC removal (Y_1), the percent TN removal (Y_2), the biogas yield (Y_3), and TSS the residual (Y_4) were 31.79%, 53.15%, 32.90 mL/min, and 28.90 mg/L, respectively. Thus, because all adequate precision values were greater than 4.00, the developed models can be used to navigate the BBD space (Ghafoori et al., 2015). Moreover, the models lack of fit p -values were calculated to be 0.1318, 0.1296, 0.2950, and 0.1501 for the percent TOC removal (Y_1), TN removal (Y_2), biogas yield (Y_3), and TSS residual (Y_4), respectively. Consequently, a not significant lack of fit ($p > 0.10$) is desirable, indicating the model fits the data well.

Table 5.4. ANOVA of the prediction results for the percent TOC and TN removal, Biogas yield, and TSS residual by quadratic modeling.

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Source	Sum of squares	df^a	Mean square	F value ^b	p -value (Prob. > F) ^c	Remark
TOC _{removal} model	452.28	9	50.254	85.835	<0.0001	Significant
X_1	254.93	1	254.93	435.42	<0.0001	Significant
X_2	49.402	1	49.402	84.380	<0.0001	Significant
X_3	2.7613	1	2.7613	4.7163	0.0664	
X_1X_2	39.125	1	39.125	66.827	0.0001	Significant
X_1X_3	6.6306	1	6.6306	11.325	0.0120	Significant
X_2X_3	28.998	1	28.998	49.530	0.0002	Significant
X_1^2	10.067	1	10.067	17.195	0.0043	Significant
X_2^2	15.867	1	15.867	27.102	0.0012	Significant
X_3^2	37.800	1	37.800	64.563	0.0001	Significant
Residual	4.0983	7	0.5855			
Lack of Fit	2.9539	3	0.9846	3.442	0.1318	Not significant
Pure error	1.1444	4	0.2861			
Corrected total SS ^d	456.38	16				
R^2	0.9910					
Adjusted R^2	0.9795					
Adequate Precision	31.793					
TN _{removal} model	3400.3	9	377.81	207.34	<0.0001	Significant
X_1	590.82	1	590.82	324.25	<0.0001	Significant
X_2	690.62	1	690.62	379.02	<0.0001	Significant
X_3	11.092	1	11.092	6.0874	0.0430	Significant
X_1X_2	220.82	1	220.82	121.19	<0.0001	Significant
X_1X_3	168.09	1	168.09	92.250	<0.0001	Significant
X_2X_3	0.4970	1	0.4970	0.2728	0.6176	Not significant
X_1^2	99.553	1	99.553	54.636	0.0002	Significant
X_2^2	38.593	1	38.593	21.180	0.0025	Significant
X_3^2	1493.7	1	1493.7	819.76	<0.0001	Significant
Residual	12.755	7	1.8221			
Lack of Fit	9.2245	3	3.0748	3.4838	0.1296	Not significant
Pure error	3.5304	4	0.8826			
Corrected total SS ^d	3413.0	16				
R^2	0.9963					
Adjusted R^2	0.9915					
Adequate Precision	53.145					
Biogas yield model	3693.0	9	410.33	122.09	<0.0001	Significant
X_1	548.80	1	548.80	163.29	<0.0001	Significant
X_2	15.596	1	15.596	4.6405	0.0682	
X_3	250.99	1	250.99	74.680	0.0001	Significant
X_1X_2	289.34	1	289.34	86.090	<0.0001	Significant
X_1X_3	183.33	1	183.33	54.549	0.0002	Significant
X_2X_3	26.368	1	26.368	7.8456	0.0265	Significant
X_1^2	0.5063	1	0.5063	0.1506	0.7095	Not significant
X_2^2	1549.6	1	1549.6	461.08	<0.0001	Significant
X_3^2	694.09	1	694.09	206.52	<0.0001	Significant
Residual	23.526	7	3.3609			
Lack of Fit	13.355	3	4.4516	1.7506	0.2950	Not significant
Pure error	10.172	4	2.5429			
Corrected total SS ^d	3716.5	16				
R^2	0.9937					
Adjusted R^2	0.9855					
Adequate Precision	32.903					

Source	Sum of squares	df ^a	Mean square	F value ^b	p-value (Prob. > F) ^c	Remark
TSS _{residual} model	557.45	9	61.940	77.160	<0.0001	Significant
X ₁	86.860	1	86.860	108.20	<0.0001	Significant
X ₂	202.01	1	202.01	251.65	<0.0001	Significant
X ₃	44.180	1	44.180	55.040	0.0001	Significant
X ₁ X ₂	27.040	1	27.040	33.690	0.0007	Significant
X ₁ X ₃	9.1800	1	9.1800	11.440	0.0117	Significant
X ₂ X ₃	1.6400	1	1.6400	2.0400	0.1962	Not significant
X ₁ ²	10.480	1	10.480	13.050	0.0086	Significant
X ₂ ²	1.5500	1	1.5500	1.9400	0.2067	Not significant
X ₃ ²	170.98	1	170.98	213.01	<0.0001	Significant
Residual	5.6200	7	0.8000			
Lack of Fit	3.9400	3	1.3100	3.1200	0.1501	Not significant
Pure error	1.6800	4	0.4200			
Corrected total SS ^d	563.07	16				
R ²	0.9900					
Adjusted R ²	0.9772					
Adequate Precision	28.902					

^a Degrees of freedom (*df*)

^b Fisher's (*F*) exact test value.

^c A probability value (*p*) < 0.05 is considered significant, a *p*-value > 0.10 is considered not significant.

^d Total sum of squares corrected for the mean.

Additionally, the model goodness of fit was validated by the determination coefficient (R^2) and the adjusted R^2 , which ensures the adequate variation of the quadratic model in terms of the experimental values. R^2 and adjusted R^2 values for the percent TOC removal (Y_1), the percent TN removal (Y_2), biogas yield (Y_3), and TSS residual (Y_4) were 0.9910 and 0.9795, 0.9963 and 0.9915, 0.9937 and 0.9855, and 0.9900 and 0.9772, respectively. Thus, the obtained R^2 and adjusted R^2 values for each model represent a high model significance.

5.3.4. Individual effects of model parameters

The significance of each model parameter was also evaluated using the *F*-exact test and *p*-values for each factor including linear, quadratic, and cross-factor interaction. As shown in Table 5.4, *p*-values lower than 0.05 identify model coefficients as significant. Therefore, the influent TOC concentration (X_1) showed a significant effect on all responses.

The flow rate (X_2) demonstrated a significant effect on the percent TOC removal (Y_1), the percent TN removal (Y_2), and TSS residual (Y_4). Whereas, the pH (X_3) was found to be significant on the percent TN removal (Y_2), biogas yield (Y_3), and TSS residual (Y_4) based on their *p*-value (Table 5.4).

Figure 5.5a illustrates the effect of the influent TOC concentration on the percent TOC removal, the percent TN removal, the biogas yield, and the TSS residual. It could be observed that the influent

TOC concentration is inversely proportional to both the percent TOC and TN removals while being directly proportional to the biogas yield and TSS residual. These results were validated by analyzing six influent TOC concentrations (50, 400, 750, 1100, 1450, and 1800 mg/L), selected and tested based on previous studies for SWW treatment (Cao and Mehrvar, 2011; Bustillo-Lecompte et al., 2013, 2014; Bustillo-Lecompte and Mehrvar, 2015).

On the other hand, Figure 5.5b depicts the effect of the feed flow rate on the percent TOC removal, the percent TN removal, the biogas yield, and the TSS residual. The predicted model results indicate that both the percent TOC and TN removals are inversely proportional to the feed flow rate, whereas there is a direct relationship between the feed flow rate and TSS residual.

Besides, an optimum flow rate is required for a maximum biogas yield. Six flow rates were used to validate the model results in the range of 15-165 mg/L), selected and tested based on previous studies (Rajakumar et al., 2011; Bustillo-Lecompte et al., 2013, 2014), as shown in Figure 5.5b.

Finally, Figure 5.5c portrays the influence of pH adjustment on both the percent TOC and TN removals as well as on the biogas production and TSS residual. The predicted models demonstrate that to achieve a maximum percent TOC removal, the percent TN removal, and the biogas yield with minimum TSS residual, an optimum pH value is required. These trends were confirmed by evaluating six pH levels, selected based on previous studies (Al-Mutairi et al., 2008; De Nardi et al., 2011; Rajakumar et al., 2011). Consequently, it could be stated that the influent TOC concentration, the flow rate, and the pH are found to be factors of interest to be assessed by RSM.

5.3.5. Interaction of model parameters, 2D contour plots, and 3D response surface

As shown in Table 5.4, there was only one interaction in model parameters, between the feed flow rate and the pH (X_2X_3), which indicated no significant effect on the percent TN removal and TSS residual, despite the fact that it was significant on both the TOC removal and the biogas yield simultaneously. Thus, it could be stated that the individual parameters are mainly influencing the trend for the TN removal and TSS residual as linear effects. Conversely, the cross-factor interaction of the influent TOC concentration with pH (X_1X_3) was found to have a high significant effect on both the percent TN removal and the TSS residual. The cross-factor interactions between independent variables were plotted into the 2D contour plots and 3D surfaces shown in Figure 5.6.

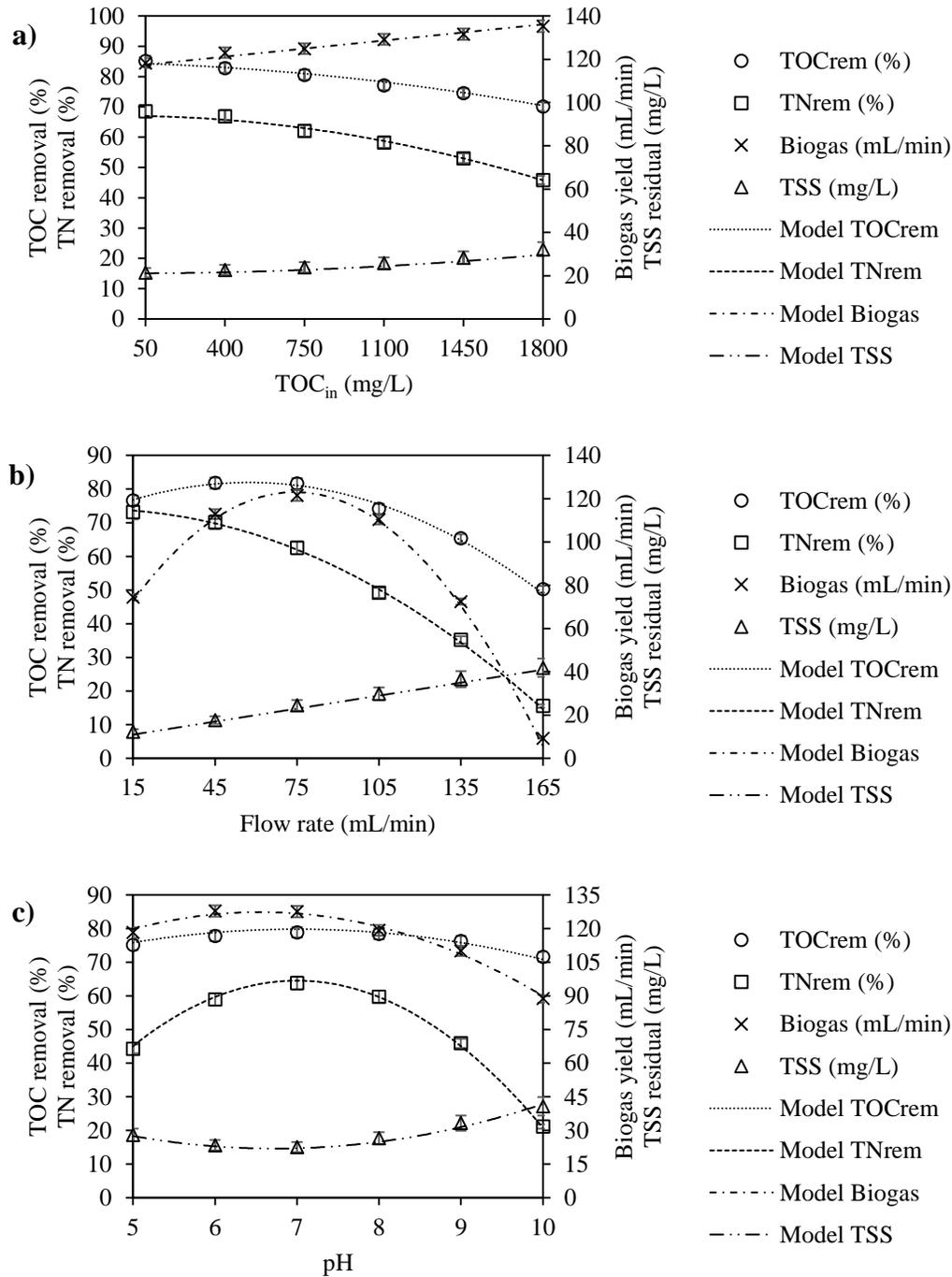


Figure 5.5. Individual effect of the (a) influent concentration of TOC, (b) flow rate, and (c) pH on percent TOC removal, percent TN removal, biogas yield, and TSS residual. The dashed lines represent model predicted values, whereas the marker points represent the experimental values. Error bars represent the standard deviation of the experimental data.

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As illustrated in Figures 5.6a, b, and c, the cross-factor interaction effects between the influent TOC concentration and the feed flow rate (X_1X_2) on the percent TOC removal (Figure 5.6a), the percent TN removal (Figure 5.6b), and the TSS residual (Figure 5.6c) were examined. It could be inferred that a desirable interaction to reach maximum TOC and TN removal with minimum TSS residual is achieved when both the influent TOC concentration and the feed flow rate are minimum. In the case of the biogas yield, it is necessary to have a high influent TOC concentration at an optimum value for the feed flow rate, near the center point within the factor range, similar to the trend shown in Figure 5.6f.

On the other hand, Figure 5.6d, e, and f depict the cross-factor interaction effects between the influent TOC concentration and the pH (X_1X_3) on the percent TOC removal (Figure 5.6d), the percent TN removal (Figure 5.6e), and the biogas yield (Figure 5.6f). Results show that a desirable interaction to reach maximum TOC and TN removal is achieved when there is an optimum value for the pH near the center point within the factor range, and the influent TOC concentration is minimum. For biogas yield, it is necessary to have a high influent TOC concentration similar to the trend for the cross-factor interaction effects between the influent TOC concentration and the feed flow rate (X_1X_2).

Finally, the cross-factor interaction effects between the feed flow rate and the pH (X_2X_3) on the biogas yield and TSS residual were illustrated in Figures 5.6g and h, respectively. It is revealed that a desirable interaction to reach maximum biogas yield is achieved when there is an optimum value for both the feed flow rate and the pH near the center points within the factor ranges (Figure 5.6g). Conversely, to reach the desired minimum TSS residual, there is an optimum value of pH near the center points within the factor ranges at low influent TOC concentrations (Figure 5.6h).

5.3.6. Optimization of operating conditions and process parameters

The RSM was used to determine the optimum experimental conditions of the three independent variables, including the influent concentration of TOC (X_1), the flow rate (X_2), and the pH (X_3) to obtain maximum percent TOC removal (Y_1), maximum percent TN removal (Y_2), and maximum biogas yield (Y_3), with minimum TSS residual (Y_4). The optimization was accomplished at defined optimization conditions using the built-in numerical optimization method of the statistical software Design-Expert 9.0.4.1. Equations (5.3) to (5.6) were defined as objective functions whereas the independent factors in their critical range were used as constraints.

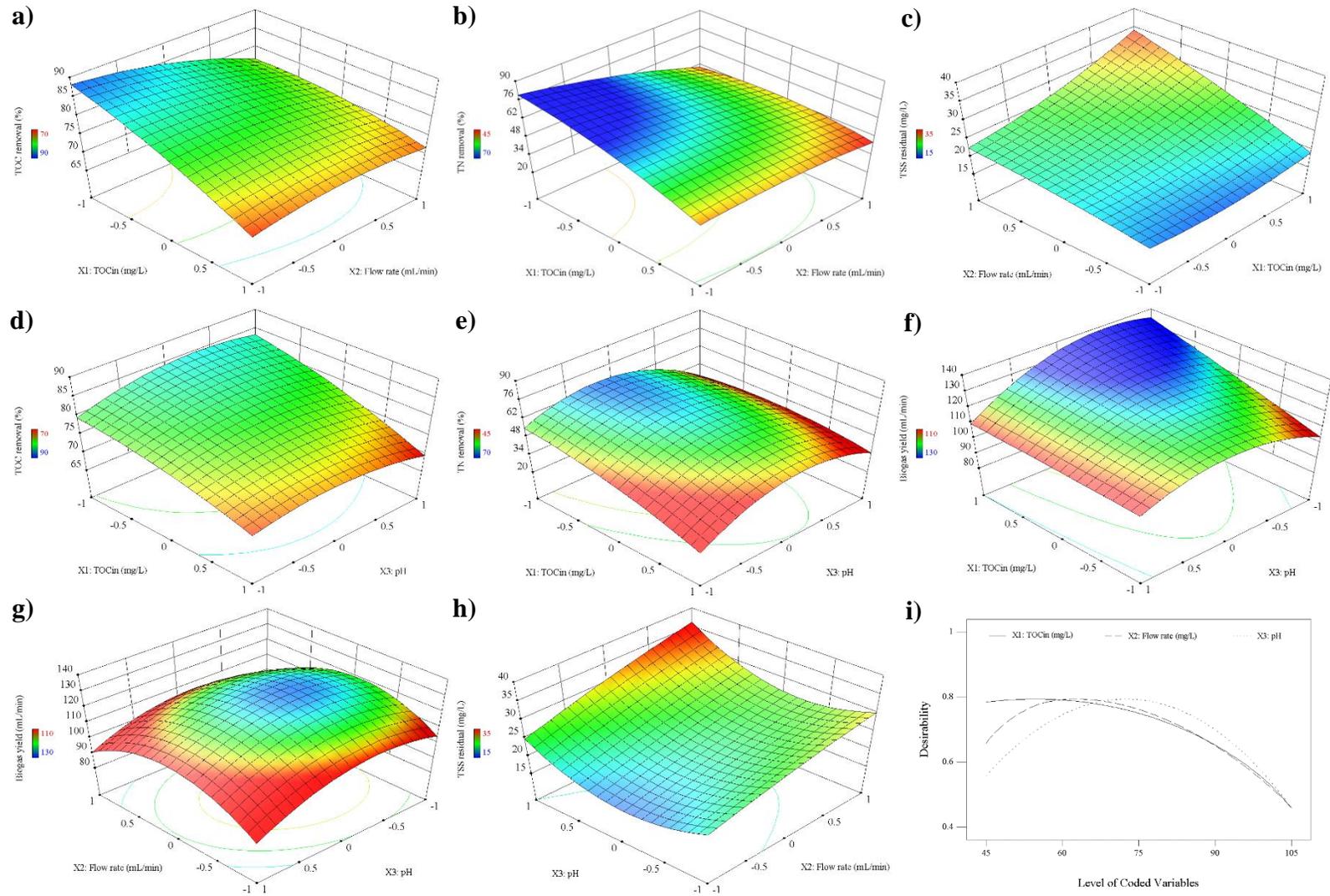


Figure 5.6. 3D plots of the cross-factor interaction effect between the influent TOC concentration and the feed flow rate (X_1X_2) on: (a) percent TOC removal (b) percent TN removal, and (c) TSS residual; interaction effect between the influent TOC concentration and pH (X_1X_3) on: (d) TOC removal, (e) TN removal, and (f) biogas yield; interaction effect between the feed flow rate and pH (X_2X_3) on: (g) biogas yield and (h) TSS residual; and (i) the desirability parameter interaction.

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The numerical optimization method explores the design space using the developed models to find the optimum factor conditions that meet the previously set goals of maximum percent TOC removal, maximum percent TN removal, and maximum biogas yield, with minimum TSS residual, simultaneously. The multiple response approach shown in Equation (5.2) was used to obtain the desirability parameter interaction plot (Figure 5.6i) at optimum factor settings by maximizing the percent TOC removal (d_1), the percent TN removal (d_2), and the biogas yield (d_3), and minimizing the TSS residual (d_4). Numerical optimization was used to maximize the biogas yield and the percent removals of TOC and TN while minimizing the TSS residual. Therefore, the desirability value of 0.79 was found to achieve the maximum removals of 85.03 and 72.10% for TOC and TN, respectively, minimum TSS residual of 19.54 mg/L, and maximum biogas yield of 116.56 mL/min at the optimum conditions of influent TOC concentration of 343 mg/L, feed flow rate of 63 mL/min, and pH of 6.84.

As a final point, the obtained optimal operating conditions were used in another experimental run to validate the predicted values. Consequently, the TOC removal of 84.92%, the TN removal of 70.61%, the TSS residual of 19.76 mg/L, and the biogas yield of 114.88 mL/min were obtained experimentally. Thus, confirming the reliability of the model since all model parameters are within the 95% confidence intervals of 80.80–89.26% for TOC removal, 64.63–79.57% for TN removal, 14.58–24.50 mg/L for TSS residual, and 106.42–126.71 mL/min for biogas yield.

5.3.7. Economic analysis

In this study, 84.92% of the influent TOC concentration of 343 mg/L were removed at the optimal feed flow rate of 63 mL/min. Thus, the rate of the TOC removal per time was 18.35 mg/min. On the other hand, the optimum biogas yield was 114.88 mL/min. These values were in line to those found in the literature for lab-scale biogas reactors (Liu et al., 2004; Kaparaju et al., 2009; Cadena Pereda et al., 2010). Hence, the total biogas production could be expressed in terms of TOC degraded:

$$\frac{\text{mL biogas}}{\text{mg TOC removed}} = \frac{114.88 \text{ mL biogas / min}}{18.35 \text{ mg TOC / min}} = 6.260 \text{ mL biogas / mg TOC} \quad (5.7)$$

Using the methane volume percentage of 35.43% obtained by biogas analysis (Landtec Biogas 5000, Colton, CA), the CH₄ production was 2.21 L/kg TOC removed. Consequently, by considering the lower heating value of methane of 35.9 MJ/m³, a daily energy generation of 0.58 kWh is obtained.

According to de Mes et al. (2003), biological processes for wastewater treatment have low energy requirements (0.01–0.10 kWh/m³). In this case, 0.01 kWh is required for the combined ABR–AS system, representing only 2% of the generated power. Figure 5.7 compares the operational costs for the individual ABR and AS processes with those of the combined ABR–AS system in terms of cost per cubic meter of the treated SWW versus the overall TOC removal. The costs related to installation and commissioning were not considered because the potential users in the meat processing industry must evaluate these particular costs separately in a case-by-case basis, depending on the number and type of animals being slaughtered per day, frequency in the cleaning of the facilities, and size of the meat processing plant. Therefore, the power consumption was used for each process multiplied by the electricity rate. A minimum overall treatment cost of 0.09 \$/m³ of actual SWW for a maximum TOC removal of 90% was achieved at the optimum operating conditions.

It is confirmed that the overall operational costs increase with the TOC removal because of the electricity consumption, especially in the AS process alone due to aeration, reaching values of up to five times higher than those of the combined ABR–AS system. Conversely, the costs have an inverse trend in the ABR process due to the potential energy recovery from CH₄ production but the maximum removals were lower than 84%. According to the Ontario Energy Board (OEB, 2016), the market price of electricity based on tiered prices for up to 750 kWh in May 1, 2016 was 0.10 \$/kWh. Thus, the laboratory scale combined ABR–AS system could generate 0.06 \$/day. These values will be representative as a base for future studies on process optimization, modeling, and scale-up.

5.4. Conclusions

Results from the three-factor, three-level BBD to evaluate the treatment of SWW by the combined ABR–AS system demonstrated the influent TOC concentration showed significant effects on all responses including percent TOC removal, TN removal, TSS residual, and biogas yield. The feed flow rate was found to be significant on the percent TOC removal, TN removal, and TSS residual; and the pH was found to be significant on percent TN removal and biogas yield. There was only one cross-factor interaction, between the feed flow rate and the pH, which showed no significant effect on two responses, percent TN removal and TSS residual, despite the fact that it was significant on TOC removal and biogas yield simultaneously. Accordingly, individual factors are influencing the trend for the TN removal and TSS residual as individual effects.

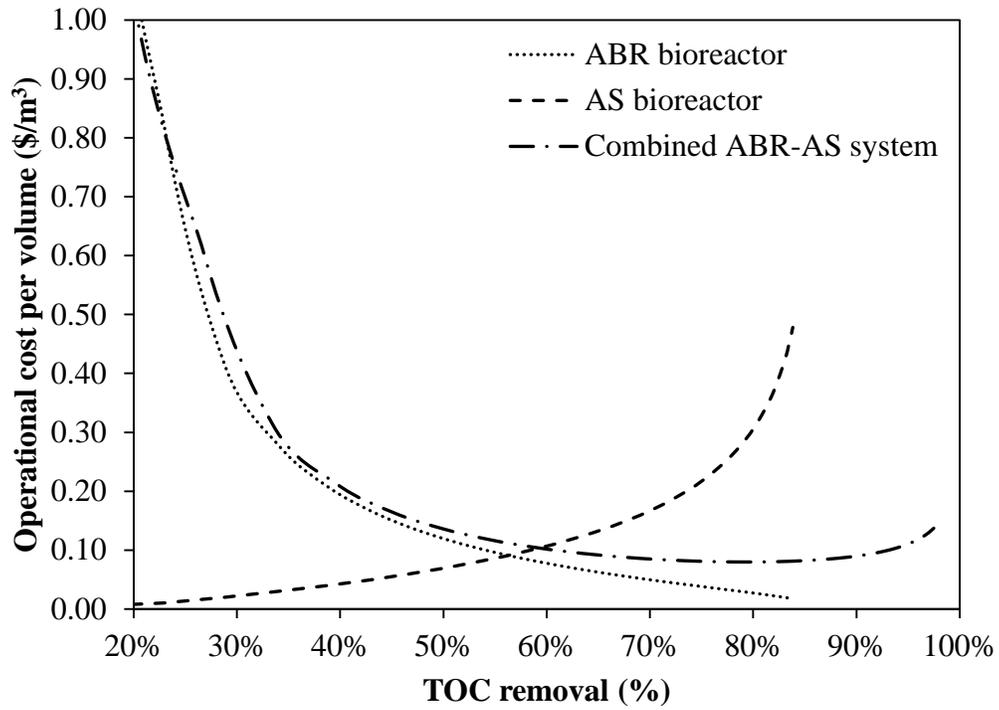


Figure 5.7. Operational costs per cubic meter of treated actual slaughterhouse wastewater against TOC removal efficiency: comparison of individual ABR and AS processes with the combined ABR–AS system in continuous mode.

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On the other hand, a desirable interaction to reach maximum TOC and TN removal with minimum TSS residual is achieved when both the influent TOC concentration and the feed flow rate are minimum, for biogas yield it is necessary a high influent TOC concentration at an optimum value for the feed flow rate. Furthermore, a maximum TOC and TN removal with minimum TSS residual is achieved when there is an optimum value for the pH, and the influent TOC concentration is minimum. Likewise, a desirable interaction to reach maximum TOC and for biogas yield is achieved when there is an optimum value for both the feed flow rate and pH.

Maximum removals of 85.03 and 72.10% for TOC and TN, respectively, minimum TSS residual of 19.54 mg/L, and maximum biogas yield of 116.56 mL/min were found at optimum conditions. The methane production was 2.21 L/kg TOC removed, equivalent to a daily energy generation of 0.58 kWh. Thus, becoming a cost-effective alternative and simultaneously beneficial to the environment. The developed statistical models provided a detailed exploration of the simultaneous cross-factor interactive effects of the influent TOC concentration, the feed flow rate, and the pH. Therefore, the proposed models explaining slaughterhouse wastewater treatment by combined anaerobic–aerobic processes for biogas production and organics removal could be used as a base for future studies for the reduction of operating costs while providing high-quality treated wastewater for water reuse in the meat processing industry.

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CHAPTER 6

PHOTOCHEMICAL DEGRADATION

OF AN ACTUAL SLAUGHTERHOUSE WASTEWATER

BY CONTINUOUS UV/H₂O₂ PHOTOREACTOR WITH RECYCLE*

Abstract

Slaughterhouse wastewater is treated using the UV/H₂O₂ process in a continuous photoreactor with recycle, in which the effect of the recycle ratio (the ratio of recycle flow rate to the main feed flow rate) on the photoreactor efficiency is investigated. A four-factor, five-level central composite design along with response surface methodology is used to maximize the total organic carbon removal from an actual slaughterhouse wastewater and minimize the H₂O₂ residual in the effluent. The effects of the flow rate and the influent concentrations of total organic carbon and H₂O₂ on the photodegradation of the actual slaughterhouse wastewater are also investigated. Statistical models are developed to predict both the total organic carbon removal and the H₂O₂ residual as response variables. The recycle ratio is found to be significant in minimizing the H₂O₂ residual and the cross-factor interactions of recycle ratio with other variables demonstrate a significant effect on both total organic carbon removal and H₂O₂ residual. A maximum total organic carbon removal of 81% and a minimum H₂O₂ residual of less than 2% are found at optimum operating conditions of 24 mg/L influent total organic carbon, 860 mg/L influent H₂O₂ concentration, 15 mL/min flow rate, and 0.18 recycle ratio. The model is validated under optimal operating conditions based on the experimental design results. The good agreement between model predictions and experimental values indicates that the proposed model could successfully describe the photochemical treatment of actual slaughterhouse wastewater by the continuous UV/H₂O₂ process with recycle and its applicability as a post-treatment method.

Keywords: Slaughterhouse wastewater, advanced oxidation processes, recycle effect, UV/H₂O₂, central composite design, experimental design.

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C. Bustillo-Lecompte, S. Ghafoori, and M. Mehrvar (2016) Photochemical degradation of an actual slaughterhouse wastewater by continuous UV/H₂O₂ photoreactor with recycle. *Journal of Environmental Chemical Engineering* 4 (1), pp. 719-732. With permission from Elsevier. License Number 3830960158225. DOI: 10.1016/j.jece.2015.12.009.

6.1. Introduction

The global production of beef, pork, and poultry meat has been doubled in the past decade and is projected to grow until 2050. Furthermore, the number of slaughterhouse facilities are increasing, which results in an expected higher volume of slaughterhouse wastewater (SWW) to be treated. The SWW is typically assessed in terms of bulk parameters because of the diverse pollutant loads in the SWW derived from the type and number of animals slaughtered that fluctuate amid the meat industry (Bustillo-Lecompte and Mehrvar, 2015). SWW usually contain high levels of organics and nutrients, expressed as bulk components such as biochemical oxygen demand (BOD), chemical oxygen demand (COD), and total organic carbon (TOC). Thus, SWW is considered detrimental worldwide, and on-site treatment would be the best option to treat and disinfect the effluents to be discharged safely into receiving waters (Debik and Coskun, 2009; Wu and Mittal, 2011; Bustillo-Lecompte et al., 2013, 2014; Bustillo-Lecompte and Mehrvar, 2015).

Advanced oxidation processes (AOPs) are becoming an attractive alternative over conventional treatment and a complimentary treatment option, as either pre-treatment or post-treatment, to current biological processes for SWW treatment (De Sena et al., 2009; Luiz et al., 2009; Cao and Mehrvar, 2011; Wu and Mittal, 2011; Barrera et al., 2012; Bustillo-Lecompte et al., 2013, 2014). Furthermore, AOPs may inactivate microorganisms without adding additional chemicals to the SWW, avoiding the formation of hazardous by-products (De Sena et al., 2009; Luiz et al., 2009; Cao and Mehrvar, 2011; Barrera et al., 2012; Bustillo-Lecompte et al., 2015).

Several AOPs have been tested for SWW treatment including ozonation, gamma radiation, and UV/H₂O₂ (Wu and Doan, 2005; Melo et al., 2008; De Sena et al., 2009; Luiz et al., 2009; Cao and Mehrvar, 2011; Barrera et al., 2012; Bustillo-Lecompte et al., 2014; Bustillo-Lecompte et al., 2015). However, the UV/H₂O₂ process has been found to be more efficient for SWW treatment. The UV/H₂O₂ process is five times faster in inactivation and inhibition of microorganisms as well as in degrading aromatic compounds than other technologies. Removal efficiencies of up to 97, 95, and 75% could be achieved by the UV/H₂O₂ process for COD, BOD, and TOC, respectively (De Sena et al., 2009; Luiz et al., 2009; Cao and Mehrvar, 2011; Wu and Mittal, 2011; Barrera et al., 2012; Bustillo-Lecompte et al., 2013, 2014). Thus, AOPs might be considered to enhance the SWW quality for water reuse purposes.

On the other hand, AOPs are considered multifactor systems due to the interaction of several parameters including organics concentration, light source intensity, oxidant concentration, reaction time, pH, and output power. Therefore, the characterization of such systems requires the consideration of cross-factor and single-factor effects using the design of experiments (DOE) to identify those factors that influence the multivariable system (Ghafoori et al., 2015).

The optimization of parameters by conventional methods needs time, materials, and a large number of experiments. On the other hand, parameters such as H₂O₂ residuals, known to be toxic to microorganisms in biological post-treatment, and recycle ratio, known as the ratio of recycle flow rate to the main feed flow rate, are not widely investigated. Moreover, conventional methods fail to consider the combined effects of all the factors involved. Therefore, a DOE is used to overcome the limitations of conventional methods and consequently optimize the factors involved. Conversely, the response surface methodology (RSM) has been recognized to be statistically reliable to analyze multifactor systems in chemical treatment processes. RSM considers cross-factor interactions to attain optimal responses using the minimum number of experiments (Ghafoori et al., 2012, 2014a, 2015).

In this study, the effects of the recycle ratio, the flow rate, and the influent concentrations of TOC and H₂O₂, and their interactions on the photochemical treatment of SWW in a UV/H₂O₂ photoreactor with recycle were investigated to evaluate its feasibility as a post-treatment method. The DOE was used to optimize the photochemical treatment of the SWW using UV/H₂O₂ process in a continuous photoreactor with recycle by maximizing the TOC removal and minimizing the H₂O₂ residual in the effluent. The optimal parametric values for the DOE were obtained using a central composite design (CCD) using four factors at five levels combined with RSM. Statistical models were also developed to predict both percent TOC removal and H₂O₂ residual as response variables by the UV/H₂O₂ process. As a final point, the statistical models were validated by an additional set of experiments carried out at optimum conditions according to the DOE results.

6.2. Materials and methods

6.2.1. Materials

Actual SWW samples were taken from selected provincially licensed meat processing plants directly from their source in Ontario, Canada, at the time of the study (OMAFRA, 2015a). SWW samples had an average TOC concentration of 862 mg/L. Table 6.1 shows the overall SWW

characteristics from the selected provincially licensed meat processing plants (Bustillo-Lecompte and Mehrvar, 2015). Three out of ten sample sites were used in this study due to the TOC low range of the slaughterhouse wastewater effluents obtained from the meat processing plants (11–94 mg/L). Distilled water (DW) was used to dilute SWW samples in order to adjust the influent TOC concentrations to different CCD levels accordingly. A hydrogen peroxide solution (30% w/w) was purchased from Sigma-Aldrich and used as received.

Table 6.1. Characteristics of the actual slaughterhouse wastewater from selected provincially licensed meat processing plants along with study range values and detection limits.

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Parameter	Range	Mean	Study range	Detection limits
BOD (mg/L)	37.95–8,231	2,649	37.95-339.5	0.000-10,000
COD (mg/L)	87.23–14,256	5,577	87.23-780.4	0.000-15,000
TN (mg/L)	6.120–339.2	156.4	6.120-54.74	0.100-25,000
TOC (mg/L)	10.51–1,718	86.21	10.51-94.01	0.100-25,000
TP (mg/L)	2.570–77.31	4.281	2.570-22.98	0.020-125.00
TSS (mg/L)	0.390–738.0	309.2	0.390-103.5	0.000-750.00
pH	6.0–7.1	6.9	6.8-7.0	4.0-10

6.2.2. Experimental setup and procedure

A laboratory-scale continuous photoreactor with recycle and uniform light distribution was used. Figure 6.1 shows the schematic diagram of the experimental setup for the UV/H₂O₂ process with recycle. The stainless steel cylindrical photoreactor (Barrier SL-1S-Siemens Inc., Markham, ON) had a total operational volume of 1.35 L with an external diameter of 8 cm and a length of 34 cm. A 2.5 cm in diameter UV-C lamp with output power of 6 W and 254 nm wavelength was inserted into the center of the photoreactor. A quartz sleeve covered the UV-C lamp to protect the lamp from fouling and maintain a uniform UV radiation emission. The following procedure was implemented to carry out each experiment for quality control:

- 1) The UV lamp was switched on for 30 min prior to the start of each experiment to guarantee light intensity stabilization within the photoreactor.
- 2) SWW samples were filtered to separate the liquid portion of the wastewater from the solids.

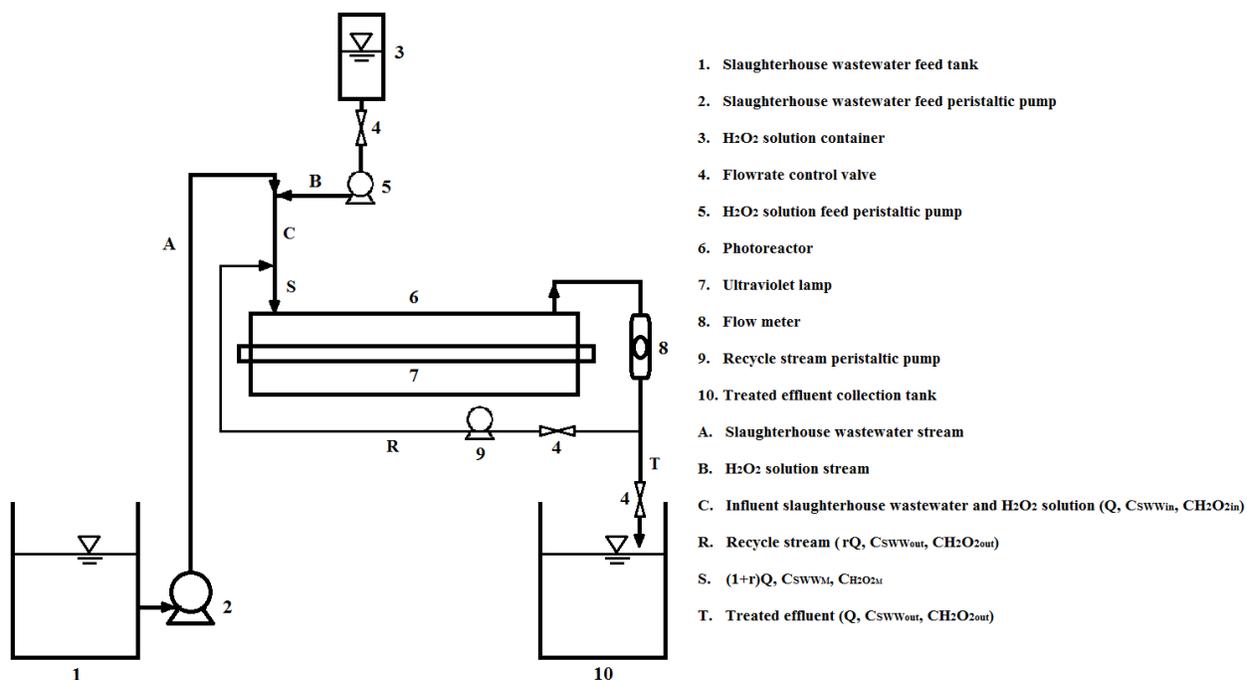


Figure 6.1. Schematic diagram of the laboratory-scale single lamp continuous UV/H₂O₂ photoreactor with effluent recycle. Q and r are the flow rate and recycle ratio, respectively. C_{SWWin} , C_{SWWout} , and C_{SWWM} are the slaughterhouse wastewater concentration in the influent, in the effluent, and entering the photoreactor, respectively. $C_{H_2O_2in}$, $C_{H_2O_2out}$, and $C_{H_2O_2M}$ are the hydrogen peroxide concentration in the influent, in the effluent, and entering the photoreactor, respectively.

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- 3) Filtered SWW samples were then diluted to reach the desired TOC concentration and guarantee the accuracy of the feed concentration value in a 6-L solution (i.e. an actual slaughterhouse wastewater sample with a concentration of 26.42 mg/L was diluted to 25.00 mg/L).
- 4) The SWW solution with the desired TOC concentration was fed to the photoreactor by a variable speed peristaltic pump to control and adjust the flow rate.
- 5) An adequate H_2O_2 concentration was calculated based on the material balance for each experiment.
- 6) The H_2O_2 solution was also fed to the system by a secondary variable speed peristaltic pump at the time the SWW solution started to be fed to the photoreactor.
- 7) A recycle stream was controlled using the third variable speed peristaltic pump to adjust the flow rate to the desired recycle ratio.
- 8) Effluent samples were taken at 15-min intervals until the system reached steady state conditions.

TOC concentration was analyzed for each sample using an automated TOC analyzer (Apollo 9000 Teledyne Tekmar, Mason, OH). The H_2O_2 residuals were measured with a UV-vis Spectrophotometer (Ultrospec 1100 pro-Amersham Biosciences, Amersham, UK) at 454 nm using neocuproine and copper (Hamad et al., 2014). All experiments were repeated in triplicates and the average values were reported. Furthermore, three replicates were made for each analytical measurement.

6.2.3. Reaction mechanisms

The UV/ H_2O_2 process uses ultraviolet radiation to cleave the O–O bond in H_2O_2 and generate hydroxyl radicals ($\cdot\text{OH}$). Subsequently, the $\cdot\text{OH}$ can be scavenged by any organic compound present in SWW to initiate a radical chain degradation of H_2O_2 in the critical chemical and photochemical reactions taking place in the UV/ H_2O_2 process (Table 6.2). All reaction mechanisms rate constants shown in Table 6.2 are based on widely accepted photochemical reactions, where the influent TOC and H_2O_2 dosage as well as other parameters are shown to have effect on the kinetics of the UV/ H_2O_2 process (Ghafoori et al., 2012). The complete mineralization of the actual SWW to H_2O and CO_2 , disregarding other intermediates, is presented in Reactions R21.

Table 6.2. Reaction mechanisms for complete mineralization of SWW by UV/H₂O₂ process.

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Number	Reaction	Rate constant	Reference
R1	$H_2O_2 \xrightarrow{\phi_{H_2O_2}, hv} 2 \cdot OH$	0.50 mol/E	Buxton et al. (1988)
R2	$H_2O_2 + \cdot OH \xrightarrow{k_2} HO_2^* + H_2O$	2.7×10^7 1/M s	Christensen et al. (1982)
R3	$HO_2^- + \cdot OH \xrightarrow{k_3} HO_2^* + OH^-$	7.5×10^9 1/M s	Christensen et al. (1982)
R4	$O_2^{\cdot -} + H_2O_2 \xrightarrow{k_4} O_2 + \cdot OH + OH^-$	0.13 1/M s	Weinstein and Bielski (1979)
R5	$O_2^{\cdot -} + H^+ \xrightarrow{k_5} HO_2^*$	1.0×10^{10} 1/M s	Bielski et al. (1985)
R6	$HO_2^* + H^+ \xrightarrow{k_6} O_2^{\cdot -} + H^+$	1.6×10^5 1/s	Bielski et al. (1985)
R7	$2 \cdot OH \xrightarrow{k_7} H_2O_2$	5.5×10^9 1/M s	Staehelin et al. (1984)
R8	$HO_2^* + O_2^{\cdot -} \xrightarrow{k_8} HO_2^- + O_2$	9.7×10^7 1/M s	Bielski et al. (1985)
R9	$O_2^{\cdot -} + \cdot OH \xrightarrow{k_9} O_2 + OH^-$	8.0×10^9 1/M s	Weinstein and Bielski (1979)
R10	$H_2O_2 \xrightleftharpoons{pK_{10}} H^+ + HO_2^-$	11.6	Weinstein and Bielski (1979)
R11	$HO_2^* + HO_2^* \xrightarrow{k_{11}} H_2O_2 + O_2$	8.3×10^5 1/M s	Bielski et al. (1985)
R12	$2HO_2^* \xrightarrow{k_{12}} H_2O_2 + O_2$	1.5×10^6 1/M s	Buxton et al. (1988)
R13	$HO_2^* + \cdot OH \xrightarrow{k_{14}} H_2O + O_2$	6.6×10^9 1/M s	Buxton et al. (1988)
R15	$H_2O_2 + HO_2^* \xrightarrow{k_{15}} H_2O + O_2 + \cdot OH$	3.00 1/M s	Koppenol et al. (1978)
R16	$HO_2^* + \cdot OH \xrightarrow{k_{16}} H_2O + O_2$	7.1×10^9 1/M s	Sehested et al. (1968)
R17	$HCO_3^- + \cdot OH \xrightarrow{k_{17}} CO_3^{\cdot -} + H_2O$	8.5×10^6 1/M s	Buxton et al. (1988)
R18	$CO_3^{2-} + \cdot OH \xrightarrow{k_{18}} CO_3^{\cdot -} + OH^-$	3.9×10^8 1/M s	Buxton et al. (1988)
R19	$CO_3^{\cdot -} + H_2O_2 \xrightarrow{k_{19}} HCO_3^- + HO_2^*$	4.3×10^5 1/M s	Crittenden et al. (1999)
R20	$TOC + \cdot OH \xrightarrow{k_{20}} intermediates \rightarrow CO_2 + H_2O$	7.0×10^5 1/M s	Barrera et al. (2012)
R21	$TOC_1 + \cdot OH \xrightarrow{k_{21}} \dots \rightarrow CO_2 + H_2O$	1.1×10^5 1/M s	Bustillo-Lecompte et al. (2016)

6.2.4. Photon irradiation balance

Uniform light distribution was considered throughout the photoreactor because of the limited annular space inside the laboratory-scale photoreactor. Consequently, by employing the photon irradiation balance, the local volumetric rate of energy absorption (LVREA) could be written based on the Beer-Lambert law (Buxton et al., 1988; Ghafoori et al., 2014b), as shown below:

$$LVREA = I_o \left(\frac{\varepsilon_{H_2O_2} [H_2O_2] + \varepsilon_{HO_2^-} [HO_2^-]}{\varepsilon_{H_2O_2} [H_2O_2] + \varepsilon_{HO_2^-} [HO_2^-] + \varepsilon_{TOC_i} [TOC_i]} \right) \times \left(1 - e^{-2.303b \{ \varepsilon_{H_2O_2} [H_2O_2] + \varepsilon_{HO_2^-} [HO_2^-] + \varepsilon_{TOC_i} [TOC_i] \}} \right) \quad (6.1)$$

where the intensity of the incident light (I_o) was calculated to be 2×10^{-5} Einstein/L.s by considering a 254 nm wavelength. The photon irradiance was estimated from the 14 W (input) low-pressure lamp per volume of the photoreactor and assuming 10% attenuation by the quartz sleeve, 33% efficiency for the low-pressure lamp, and considering the portion of the UV radiation absorption by H_2O_2 . On the other hand, $\varepsilon_{H_2O_2}$, $\varepsilon_{HO_2^-}$, and ε_{TOC_i} are the molar extinction coefficients of H_2O_2 (18.7 1/M.cm), HO_2^- (210.0 1/M.cm), and TOC_i (132.7 1/M.cm) at 254 nm, respectively. Lastly, b is the effective path length, and, in this case, is the annular space in the photoreactor.

6.2.5. Experimental design and optimization studies

A four-factor along with five-level CCD in conjunction with RSM was used to maximize percent TOC removal and minimize percent H_2O_2 residuals in the effluent. The influent concentration of TOC (X_1), influent H_2O_2 concentration (X_2), flow rate (X_3), and recycle ratio (X_4) were used as independent factors in the DOE. The percent TOC removal and H_2O_2 residual were considered as dependent factors (i.e. process responses). Thus, each factor was coded at five levels (from -2 to +2), as shown in Table 6.3. Preliminary experiments were used to determine and select the critical ranges of the factors.

Table 6.3. Independent variables with coded levels based on a four-factor, five level CCD.

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Independent variable	Symbol	Coded levels				
		-2	-1	0	1	2
TOC _{in} (mg/L)	X_1	10	25	40	55	70
H_2O_2 in (mg/L)	X_2	300	600	900	1,200	1,500
Flow rate (mL/min)	X_3	15	45	75	105	135
Recycle ratio	X_4	0.0	0.2	0.4	0.6	0.8

Equation (6.2) was used to predict the system responses as a quadratic model and estimate the parametrical coefficients by correlating dependent and independent variables using the least-squares regression (Ghafoori et al., 2012, 2014a, 2015):

$$Y = \beta_o + \sum_{i=1}^k \beta_i X_i + \sum_{i=1}^k \beta_{ii} X_i^2 + \sum_{i=1}^{k-1} \sum_{j=2}^k \beta_{ij} X_i X_j + c \quad (6.2)$$

In this equation, Y is the predicted response and β_o , β_i , β_{ii} , and β_{ij} are the constant, linear, quadratic, and cross-factor interaction coefficients, respectively. X_i and X_j represent the independent variables; whereas, k and c are the number of factors and the residual term, respectively.

The statistical software Design-Expert 9.0.4.1 was employed for graphical and regression analysis to estimate the coefficients of the response functions. Moreover, the significance of the model equations, independent variables, and factor interactions were examined by analysis of variance (ANOVA) at 95% confidence intervals (CI), i.e. $\alpha = 0.05$. Three-dimensional (3D) surfaces and two-dimensional (2D) contour plots were obtained while keeping another factor constant in the quadratic models. Experiments were carried out to validate the statistical models for maximum percent TOC removal and minimum H_2O_2 residual. Optimal operating conditions were estimated using the numerical optimization method built in the software. Lastly, an additional experimental run was carried out to validate the predicted optimal conditions for both response functions, the percent removal of TOC, and H_2O_2 residual.

The desirability multiple response method was used to combine the desirable ranges for each response in order to obtain a simultaneous objective function that represents the geometric mean of all transformed responses as shown in Equation (6.3) (Myers et al., 2004; Bustillo-Lecompte et al., 2016):

$$D = (d_1 \times d_2 \times \dots \times d_n)^{1/n} = \left(\prod_{i=1}^n d_i \right)^{1/n} \quad (6.3)$$

In this equation, D , d_i , and n are the desirability objective function, each response range, and the number of responses, respectively. If any of the analyzed responses is found to be outside of their desirability range, the overall desirability function becomes zero. Therefore, for a simultaneous optimization, each

response is required to be assigned low and high values for optimization. In this case, the percent removal of TOC (d_1) is maximized while the H_2O_2 residual (d_2) is minimized.

6.3. Results and discussion

6.3.1. Preliminary experiments

Preliminary experiments were conducted to select the critical ranges of the influent TOC concentration, the influent H_2O_2 concentration, the flow rate, and the recycle ratio based on their effects on the percent TOC removal and the H_2O_2 residual. Figure 6.2 depicts the profiles for percent TOC removal and H_2O_2 residual in a laboratory-scale single lamp continuous UV/ H_2O_2 photoreactor with recycle. Different conditions of the influent TOC concentration (Figure 6.2a), the influent H_2O_2 concentration (Figure 6.2b), the flow rate (Figure 6.2c), and the recycle ratio (Figure 6.2d) were used.

As shown in Figure 6.2a, five influent TOC concentrations (10, 30, 50, 70, 90 mg/L) were used. These influent concentrations were selected based on previous studies for the SWW treatment by UV/ H_2O_2 (De Sena et al., 2009; Luiz et al., 2009; Cao and Mehrvar, 2011; Wu and Mittal, 2011; Barrera et al., 2012; Bustillo-Lecompte et al., 2013, 2014). It can be observed that as the influent TOC concentration increases, the percent TOC removal decreases. Conversely, the H_2O_2 residual is minimum at an optimum influent TOC concentration value.

Figure 6.2b depicts the influence of the influent H_2O_2 concentration on the TOC removal and the H_2O_2 residual. Five H_2O_2 concentrations (300, 600, 900, 1200, and 1500 mg/L) were selected and tested based on previous studies (Cao and Mehrvar, 2011; Wu and Mittal, 2011; Barrera et al., 2012; Bustillo-Lecompte et al., 2013, 2014, 2015). Results show that by increasing the H_2O_2 concentration, the H_2O_2 residual also increases; whereas there is an optimum H_2O_2 concentration at which percent TOC removal is maximum.

Likewise, Figure 6.2c illustrates the effects of the flow rate on both the percent TOC removal and the H_2O_2 residual. Up to six flow rates were tested in the range of 15-165 mg/L. Results demonstrate that H_2O_2 residual is directly proportional to the flow rate while the TOC removal is inversely proportional to the flow rate as established by the profile trends.

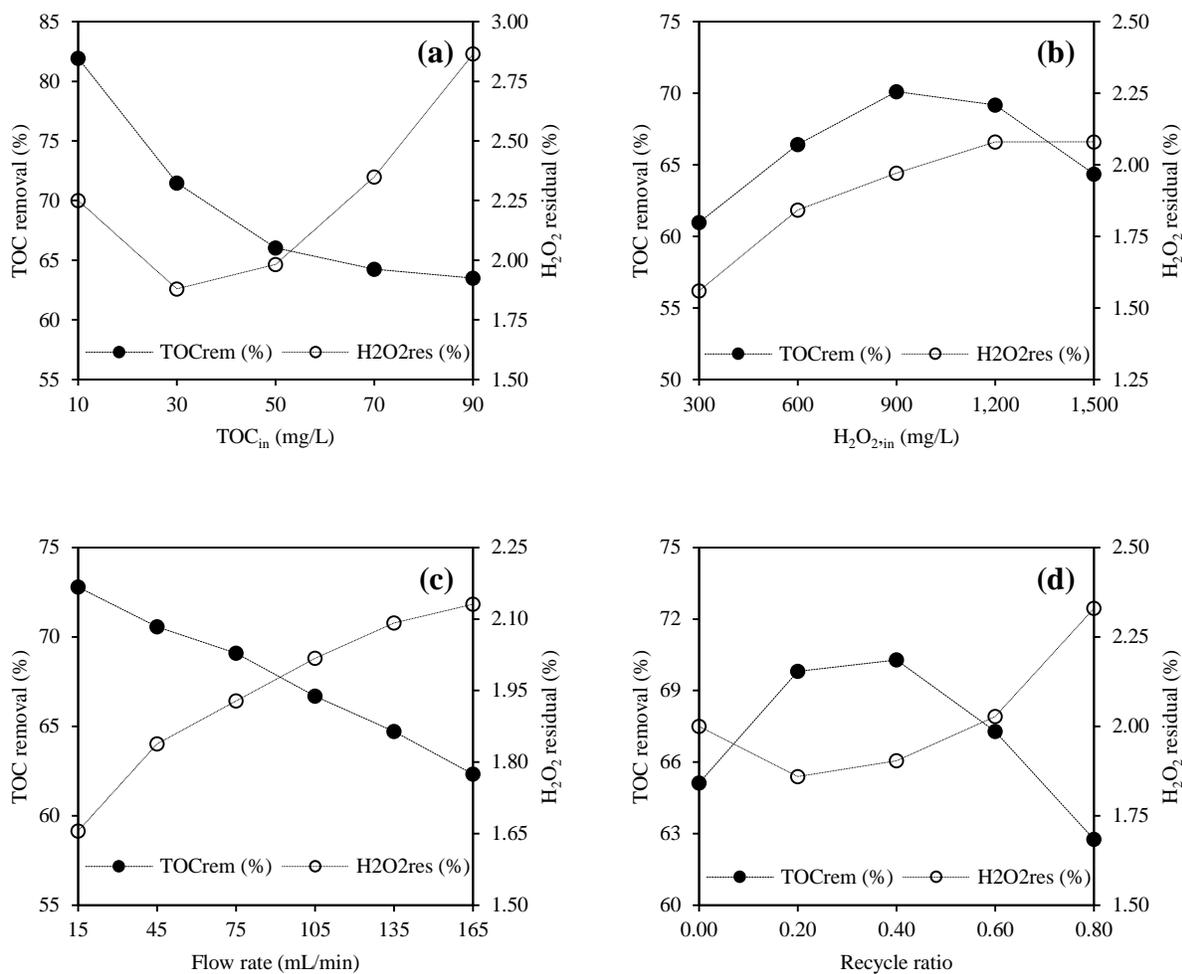


Figure 6.2. Profiles of TOC removal and H₂O₂ residual in a laboratory-scale single lamp continuous UV/H₂O₂ photoreactor with effluent recycle for SWW treatment under different conditions of (a) influent concentration of TOC, (b) influent H₂O₂ concentration, (c) flow rate, and (d) recycle ratio.

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As a final point, Figure 6.2d illustrates the profile trends of the TOC removal and the H₂O₂ residual in terms of recycle ratio. Results show that an optimum recycle ratio was required to achieve a maximum TOC removal with minimum H₂O₂ residual. Therefore, the recycle ratio was found to be a variable of interest to be evaluated using DOE and RSM.

6.3.2. Experimental design and statistical analysis

Table 6.4 portrays the four-factor, five-level CCD with observed and predicted values for both percent TOC removal and H₂O₂ residual by the developed quadratic models related to the UV/H₂O₂ process in a continuous photoreactor with recycle for SWW treatment.

Table 6.4. Four-factor, five-level CCD for RSM, along with the observed and predicted percent TOC removal and H₂O₂ residual.

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Run	Independent coded variables				TOC removal (%)		H ₂ O ₂ residual (%)	
	X ₁	X ₂	X ₃	X ₄	Observed	Predicted	Observed	Predicted
1	1	1	1	1	66.12	64.88	2.03	2.06
2	-2	0	0	0	80.43	79.88	2.25	2.21
3	-1	-1	1	-1	69.21	69.03	1.63	1.66
4	0	0	0	0	71.9	71.53	1.82	1.77
5	1	-1	1	1	60.55	61.08	1.96	2.01
6	-1	1	-1	-1	77.45	76.26	1.78	1.79
7	0	0	0	0	71.96	71.53	1.75	1.77
8	-1	1	1	1	71.94	71.83	2.35	2.37
9	0	0	0	0	72.08	71.53	1.75	1.77
10	2	0	0	0	64.39	66.51	2.35	2.30
11	-1	1	-1	1	76.17	76.38	1.87	1.88
12	0	-2	0	0	60.15	60.37	1.55	1.50
13	1	1	-1	1	66.83	66.35	1.79	1.82
14	-1	-1	1	1	71.23	70.48	2.1	2.10
15	0	0	2	0	64.7	65.99	2.17	2.12
16	1	-1	1	-1	66.79	65.68	1.78	1.80
17	1	1	1	-1	64.31	62.72	2.42	2.43
18	-1	-1	-1	1	67.09	68.01	1.97	2.03
19	0	0	0	2	63.41	63.69	2.3	2.25
20	1	-1	-1	-1	68.77	68.22	1.71	1.75
21	0	0	0	0	72.31	71.53	1.77	1.77
22	1	-1	-1	1	56.72	55.52	2.21	2.20
23	-1	-1	-1	-1	74.31	74.65	1.36	1.36
24	-1	1	1	-1	63.31	63.61	2.48	2.52
25	1	1	-1	-1	72.44	72.29	1.94	1.96
26	0	0	0	0	70.72	71.53	1.77	1.77
27	0	0	0	-2	66.89	68.18	1.99	1.95
28	0	2	0	0	64.43	65.78	2.01	1.97
29	0	0	-2	0	72.81	73.08	1.61	1.58
30	0	0	0	0	70.19	71.53	1.77	1.77

RSM was employed for parameter estimation, indicating the relationship between the input factors and the responses, as shown in Equation (6.2). Thus, in order to predict the response functions for percent TOC removal (Y_1) and H₂O₂ residual (Y_2), the following second-order polynomial equations, Equations (6.4) and (6.5), respectively, were developed in terms of the coded factors:

$$Y_1 = 71.53 - 3.34X_1 + 1.35X_2 - 1.77X_3 - 1.12X_4 + 0.62X_1X_2 + 0.77X_1X_3 - 1.52X_1X_4 - 1.76X_2X_3 + 1.69X_2X_4 + 2.02X_3X_4 + 0.42X_1^2 - 2.11X_2^2 - 0.50X_3^2 - 1.40X_4^2 \quad (6.4)$$

$$Y_2 = 1.77 + 0.02X_1 + 0.12X_2 + 0.13X_3 + 0.08X_4 - 0.05X_1X_2 - 0.06X_1X_3 - 0.06X_1X_4 + 0.11X_2X_3 - 0.15X_2X_4 - 0.06X_3X_4 + 0.12X_1^2 - 0.01X_2^2 + 0.01X_3^2 + 0.08X_4^2 \quad (6.5)$$

Negative coefficients for the model components, X_1 , X_3 , X_4 , X_1X_4 , X_2X_3 , X_2^2 , X_3^2 and X_4^2 in Y_1 and X_1X_2 , X_1X_3 , X_1X_4 , X_2X_4 , X_3X_4 , and X_2^2 in Y_2 , indicate unfavorable effects on the percent TOC removal and the H₂O₂ residual, respectively. While, positive coefficients for X_2 , X_1X_2 , X_1X_3 , X_2X_4 , X_3X_4 , and X_1^2 in Y_1 and X_1 , X_2 , X_3 , X_4 , X_2X_3 , X_1^2 , X_3^2 , and X_4^2 in Y_2 indicate favorable effects on the percent TOC removal and the H₂O₂ residual, respectively.

Coefficients with values close to zero represent lower relative intensity. Thus, X_1^2 and X_3^2 do not intensely affect the TOC removal while X_2^2 and X_3^2 do not intensely affect H₂O₂ residual. Although this evaluation provides a rapid analysis in terms of the parametrical effect on the response variables, ANOVA with 95% CI was also applied to evaluate the statistical significance of the developed quadratic models for the percent TOC removal and the H₂O₂ residual as shown in Tables 6.5 and 6.6, respectively. The statistical significance of each factor coefficient, as shown in Equations (6.4) and (6.5), was determined by the Fisher's (F) exact test, comparing probability (p) values greater than F . As shown in Tables 6.5 and 6.6, the model F -values of 35.34 and 102.08 for TOC removal and H₂O₂ residual, respectively, imply the models are significant.

Besides, small probability values ($p < 0.05$) indicate significant model terms, which confirm the accuracy of the developed models to predict the response functions. On the other hand, p -values > 0.10 indicate the model terms are not significant; in this case, X_1^2 is not significant for TOC removal while X_2^2 and X_3^2 are not significant for H₂O₂ residual. If the quadratic effect is not significant, then the optimal levels of the parameter are in the extremes of the experimental region (Beard et al., 2007; Botha et al., 2012).

Table 6.5. ANOVA results for prediction of percent TOC removal by quadratic modeling.

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Source	Sum of squares	df^a	Mean square	F value ^b	p -value (Prob. > F) ^c	Remark
Model	808.36	14	57.74	35.34	<0.0001	Significant
X_1	268.40	1	268.40	164.30	<0.0001	Significant
X_2	43.90	1	43.90	26.87	0.0001	Significant
X_3	75.40	1	75.40	46.16	<0.0001	Significant
X_4	30.15	1	30.15	18.46	0.0006	Significant
X_1X_2	6.05	1	6.05	3.70	0.0735	
X_1X_3	9.52	1	9.52	5.83	0.0290	Significant
X_1X_4	36.72	1	36.72	22.48	0.0003	Significant
X_2X_3	49.35	1	49.35	30.21	0.0001	Significant
X_2X_4	45.70	1	45.70	27.97	0.0001	Significant
X_3X_4	65.53	1	65.53	40.11	<0.0001	Significant
X_1^2	4.77	1	4.77	2.92	0.1082	Not significant
X_2^2	122.48	1	122.48	74.97	<0.0001	Significant
X_3^2	6.77	1	6.77	4.15	0.0598	
X_4^2	53.62	1	53.62	32.82	<0.0001	Significant
Residual	24.50	15	1.63			
Lack of Fit	20.82	10	2.08	2.83	0.1316	Not significant
Pure error	3.68	5	0.74			
Corrected total SS ^d	832.86	29				
R^2	0.9706					
Adjusted R^2	0.9431					
Adequate Precision	26.96					

^a Degrees of freedom (df)^b Fisher's (F) exact test value.^c A probability value (p) < 0.05 is considered significant, a p -value > 0.10 is considered not significant.^d Total sum of squares corrected for the mean.

Table 6.6. ANOVA results for prediction of percent H₂O₂ residual by quadratic modeling.

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Source	Sum of squares	<i>df</i> ^a	Mean square	<i>F</i> value ^b	<i>p</i> -value (Prob. > <i>F</i>) ^c	Remark
Model	2.21	14	0.16	102.08	<0.0001	Significant
<i>X</i> ₁	0.01	1	0.01	5.22	0.0374	Significant
<i>X</i> ₂	0.33	1	0.33	211.21	<0.0001	Significant
<i>X</i> ₃	0.39	1	0.39	252.25	<0.0001	Significant
<i>X</i> ₄	0.14	1	0.14	93.20	<0.0001	Significant
<i>X</i> ₁ <i>X</i> ₂	0.04	1	0.04	28.51	0.0001	Significant
<i>X</i> ₁ <i>X</i> ₃	0.06	1	0.06	38.81	<0.0001	Significant
<i>X</i> ₁ <i>X</i> ₄	0.06	1	0.06	37.24	<0.0001	Significant
<i>X</i> ₂ <i>X</i> ₃	0.19	1	0.19	122.34	<0.0001	Significant
<i>X</i> ₂ <i>X</i> ₄	0.36	1	0.36	232.76	<0.0001	Significant
<i>X</i> ₃ <i>X</i> ₄	0.06	1	0.06	38.81	<0.0001	Significant
<i>X</i> ₁ ²	0.41	1	0.41	267.03	<0.0001	Significant
<i>X</i> ₂ ²	0.00	1	0.00	0.94	0.3469	Not significant
<i>X</i> ₃ ²	0.00	1	0.00	2.86	0.1112	Not significant
<i>X</i> ₄ ²	0.19	1	0.19	125.01	<0.0001	Significant
Residual	0.02	15	0.00			
Lack of Fit	0.02	10	0.00	3.03	0.1162	Not significant
Pure error	0.00	5	0.00			
Corrected total SS ^d	2.23	29				
<i>R</i> ²	0.9896					
Adjusted <i>R</i> ²	0.9799					
Adequate Precision	40.93					

^a Degrees of freedom (*df*)^b Fisher's (*F*) exact test value.^c A probability value (*p*) < 0.05 is considered significant, a *p*-value > 0.10 is considered not significant.^d Total sum of squares corrected for the mean.

The goodness of fit of the model was validated by the determination coefficient (R^2) and the adjusted R^2 that ensures an adequate variation of the quadratic model to the experimental values. The values of R^2 and adjusted R^2 were found to be 0.9706 and 0.9431 for the percent TOC removal and 0.9896 and 0.9799 for the H_2O_2 residual, respectively. Thus, high R^2 and adjusted R^2 values represent a high model significance. The closer the values of R^2 and adjusted R^2 are to 1.0, the better the model prediction is.

Furthermore, the adequate precision of the percent TOC removal and H_2O_2 residual were found to be 26.96 (Table 6.5) and 40.93 (Table 6.6), respectively. Since both adequate precision values were greater than 4.00, the model can be used to navigate the CCD design space (Ghafoori et al., 2012). Moreover, the lack of fit was calculated to measure how well the model fits the data. The lack of fit p -values of the percent TOC removal and the H_2O_2 residual were found to be 0.1316 (Table 6.5) and 0.1162 (Table 6.6), respectively. An insignificant lack of fit ($p > 0.10$) is a desirable property because it indicates that the model fits the data well.

On the other hand, the assumption of the constant variance was verified by plotting the internally studentized residual versus predicted values (Figures 6.3a and 6.4a). The studentized residuals are found by dividing the residuals by their standard deviations.

Figures 6.3a and 6.4a also show randomly scattered points within the outlier detection limits – 3 and +3. Therefore, model predictions, described in Equations (6.4) and (6.5), for both the percent TOC removal and the H_2O_2 residual, respectively, are satisfactory.

Moreover, the normal probability plot of residuals, shown in Figures 6.3b and 6.4b for the TOC removal and the H_2O_2 residual, respectively, showed a straight-line pattern followed by the points on the plot, not an S-shaped curve. Consequently, a transformation of the response is not required because of the normal distribution of the residuals (Ghafoori et al., 2014a).

The correlation between observed and predicted values is shown in Figures 6.3c and 6.4c for the TOC removal and the H_2O_2 residual, respectively. As a result, low discrepancies are represented by a straight-line trend, which indicates a good agreement between observed and predicted values. Hence, the quadratic model predictions for both percent TOC removal and H_2O_2 residual responses are satisfactory.

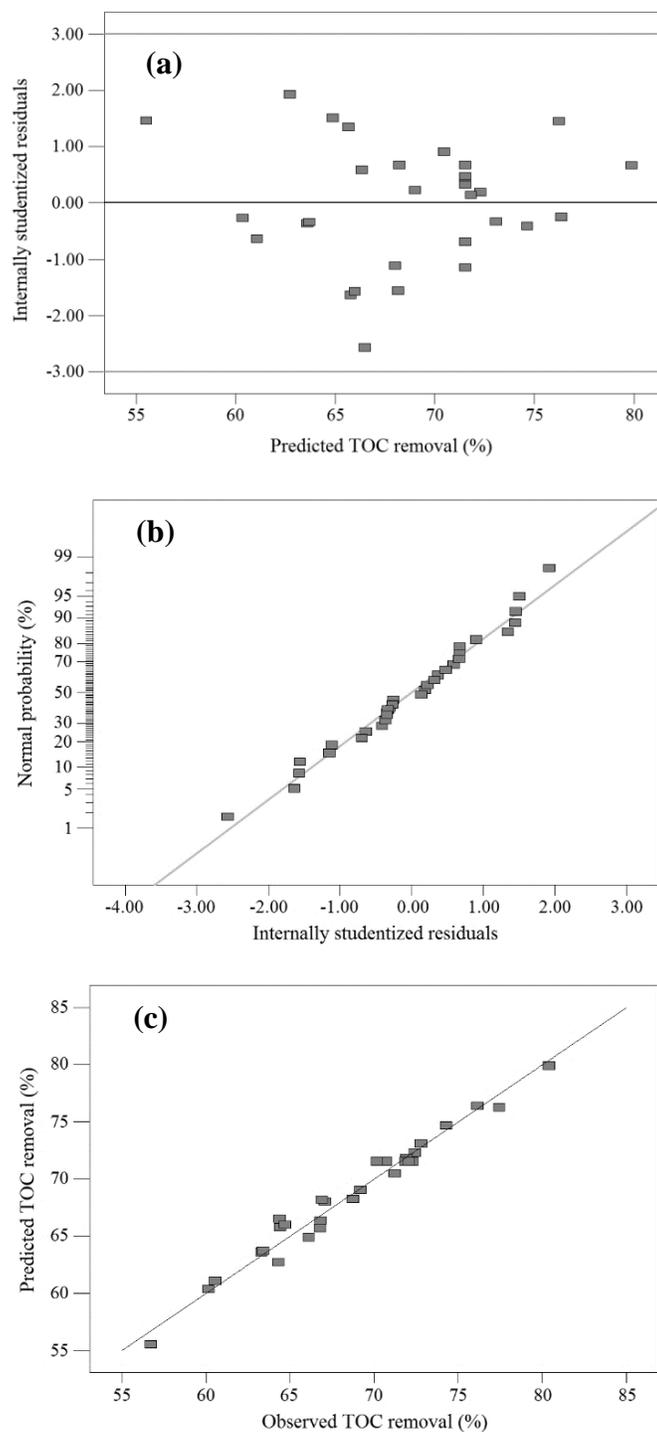


Figure 6.3. Validation of the percent TOC removal model using different plots: (a) internally studentized residuals versus predicted values, (b) normal probability, and (c) observed experimental data versus predicted values.

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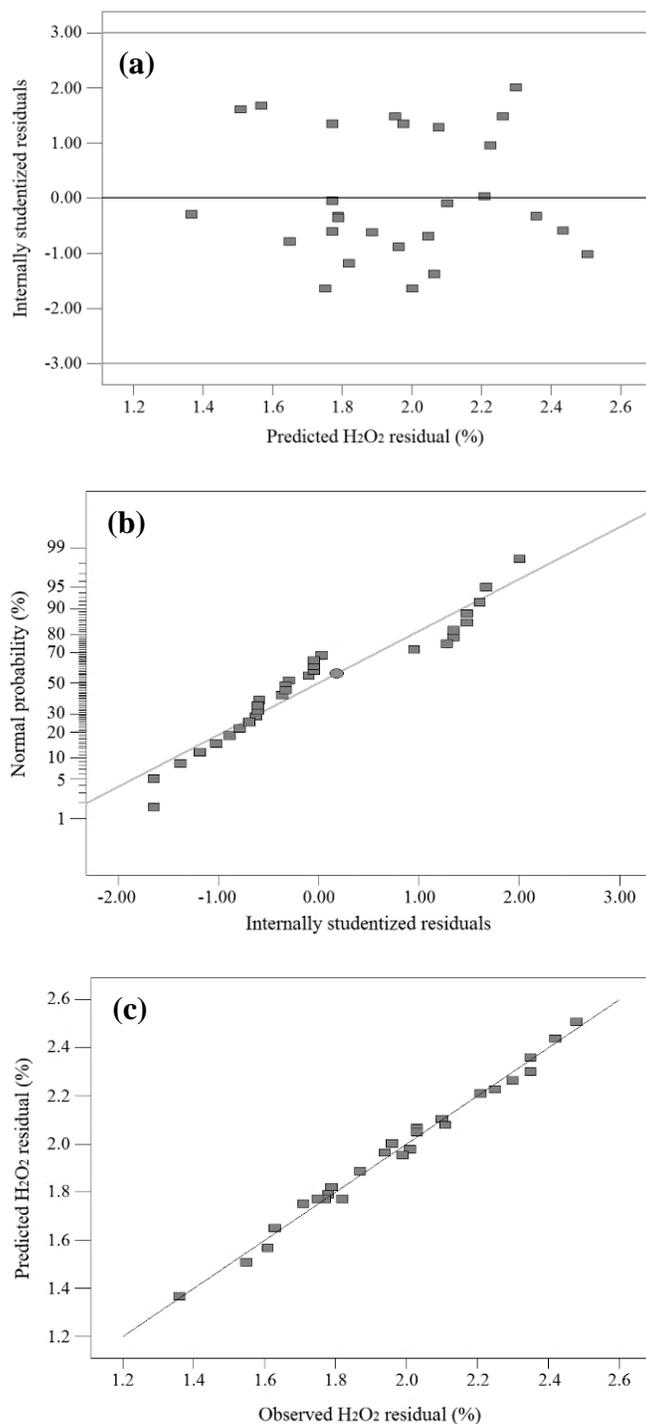


Figure 6.4. Validation of the percent H₂O₂ residual model using different plots: (a) internally studentized residuals versus predicted values, (b) normal probability, and (c) observed experimental data versus predicted values.

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6.3.3. Individual effect of model parameters

Since the significance of the models (Tables 6.5 and 6.6) and the accuracy of the model predictions (Figures 6.3 and 6.4) were confirmed, it was required to examine the significance of each model factor. This evaluation was also performed using the F exact test and p -values for each factor including linear, quadratic, and cross-factor interaction.

As presented in Tables 6.5 and 6.6, p -values lower than 0.05 indicate the significance of the model coefficients. Therefore, all four independent variables, influent TOC concentration (X_1), influent H_2O_2 concentration (X_2), flow rate (X_3), and recycle ratio (X_4), have significant effect on both responses, percent TOC removal, and H_2O_2 residual, based on their p -value.

Figures 6.5a and 6.6a depict the effect of the influent TOC concentration on the TOC removal and the H_2O_2 residual, respectively. It can be observed that the influent TOC concentration is inversely proportional to the percent TOC removal, whereas there is an optimum influent TOC concentration at which the H_2O_2 residual is minimum. Thus, this confirms the results obtained in the preliminary experiments as illustrated in Figure 6.2a.

On the other hand, Figures 6.5b and 6.6b illustrate the effect of the H_2O_2 concentration on the TOC removal and the H_2O_2 residual, respectively. The predicted models show that there is an optimum H_2O_2 concentration for a maximum percent TOC removal and a direct relationship between the influent H_2O_2 concentration and the H_2O_2 residual, confirming observed values from the preliminary studies as depicted in Figure 6.2b.

Similarly, Figures 6.5c and 6.6c show the effect of the flow rate on the percent TOC removal and the H_2O_2 residual, respectively. The predicted models confirm that the percent TOC removal is inversely proportional to the flow rate and that the H_2O_2 residual is directly proportional to the flow rate, as shown in Figure 6.2c.

Finally, Figures 6.5d and 6.6d depict the effects of the recycle ratio on the TOC removal and the H_2O_2 residual, respectively. The predicted models demonstrate that to achieve a maximum TOC removal with minimum H_2O_2 residual, an optimum recycle ratio is required.

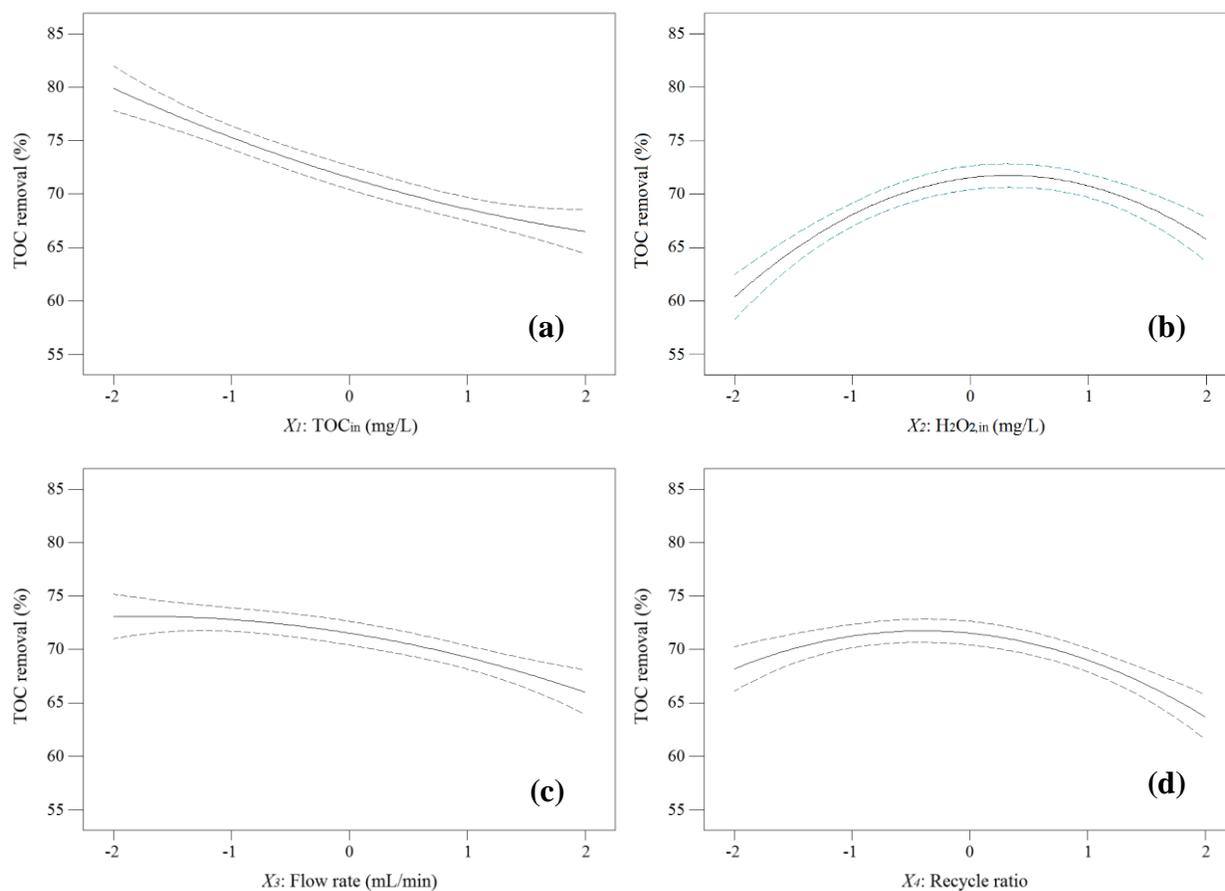


Figure 6.5. The individual effect of model parameters on the percent TOC removal: (a) influent concentration of TOC, (b) influent H₂O₂ concentration, (c) flow rate, and (d) recycle ratio. The continuous lines represent model predicted values, whereas the dashed lines represent the 95% confidence interval bands.

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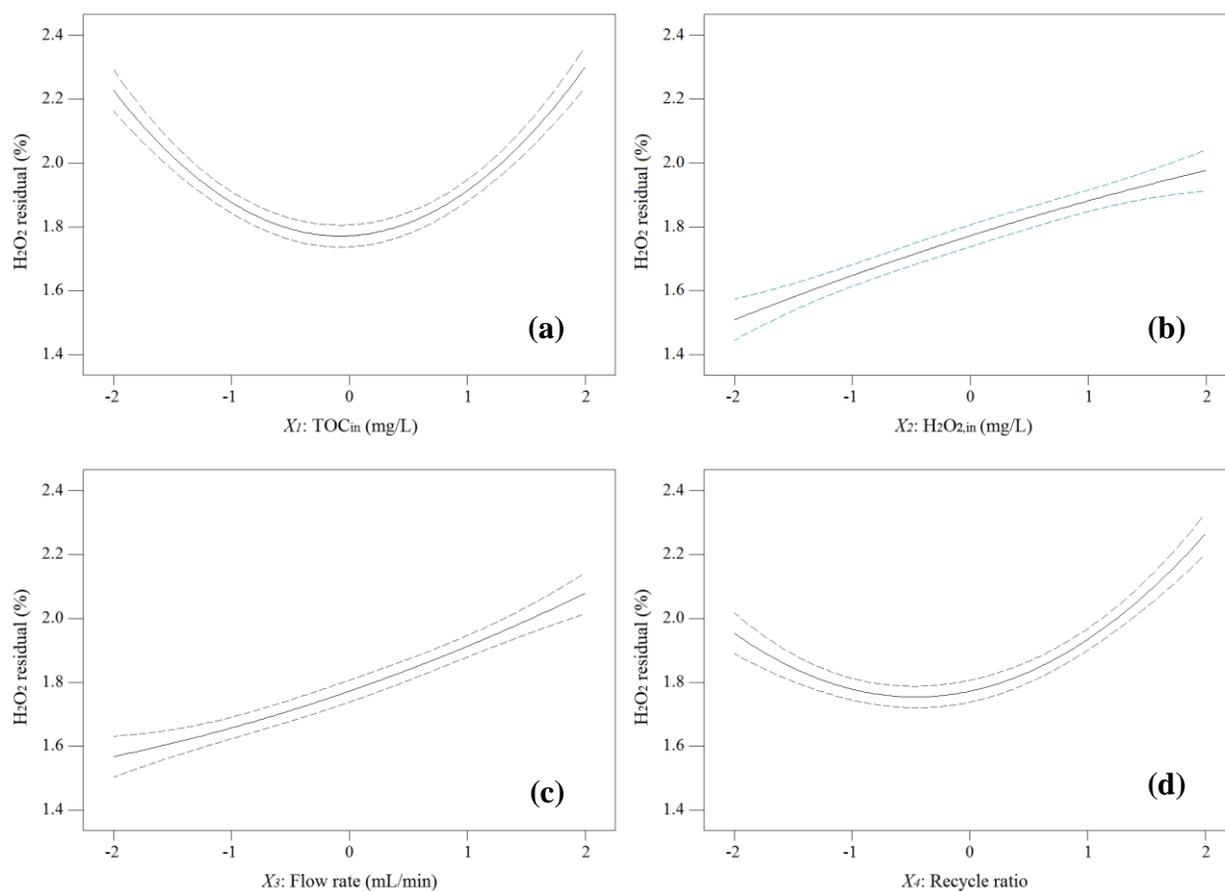


Figure 6.6. The individual effect of model parameters on the H₂O₂ residual: (a) influent concentration of TOC, (b) influent H₂O₂ concentration, (c) flow rate, and (d) recycle ratio. The continuous lines represent model predicted values, whereas the dashed lines represent the 95% confidence interval bands.

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This confirms the trends observed in preliminary experiments (Figure 6.2d) and the significance of this variable. When the recycle ratio was augmented from 0.4 to 0.6, the percent TOC removal decreased, probably due to an excess of H₂O₂ residual returning through the recycle stream, resulting in hydroxyl radical self-scavenging effect by recombination.

6.3.4. Interaction of model parameters, 2D contour plots, and 3D response surface

As shown in Tables 6.5 and 6.6, there was only one interaction among model parameters, between influent TOC and H₂O₂ concentrations (X_1X_2), which did not indicate a significant effect on the percent TOC removal, despite the fact that it was significant on the H₂O₂ residual simultaneously. Thus, it can be stated that individual parameters clearly influence the trend for the TOC removal as linear effects.

On the contrary, the cross-factor interactions of the recycle ratio with other variables, including influent TOC concentration (X_1X_4), influent H₂O₂ concentration (X_2X_4), and flow rate (X_3X_4), were found to have a high significant effect on both TOC removal and H₂O₂ residual.

The cross-factor interaction effects between independent variables were plotted into the 3D surfaces and 2D contour plots as shown in Figures 6.7 and 6.8 for the TOC removal and the H₂O₂ residual, respectively. These figures are the graphical representations of the regression analysis, where the response functions of two factors are presented while all others are at the fixed levels (Ghafoori et al., 2012, 2014a, 2015).

As shown in Figures 6.7(a–c), the percent TOC removal decreases by increasing the influent TOC concentrations within the factor range. The effect of the influent TOC concentration on the percent TOC removal is essentially attributable to the absorption of UV radiation by organic compounds along with intermediates formed during the photochemical reactions.

Hence, the penetrability of the UV light is reduced at higher TOC concentrations; thus, the UV light absorption by H₂O₂ becomes lower, causing a reduced amount of hydroxyl radicals, major contributor to the TOC reduction (Ghafoori et al., 2012, 2014a, 2015).

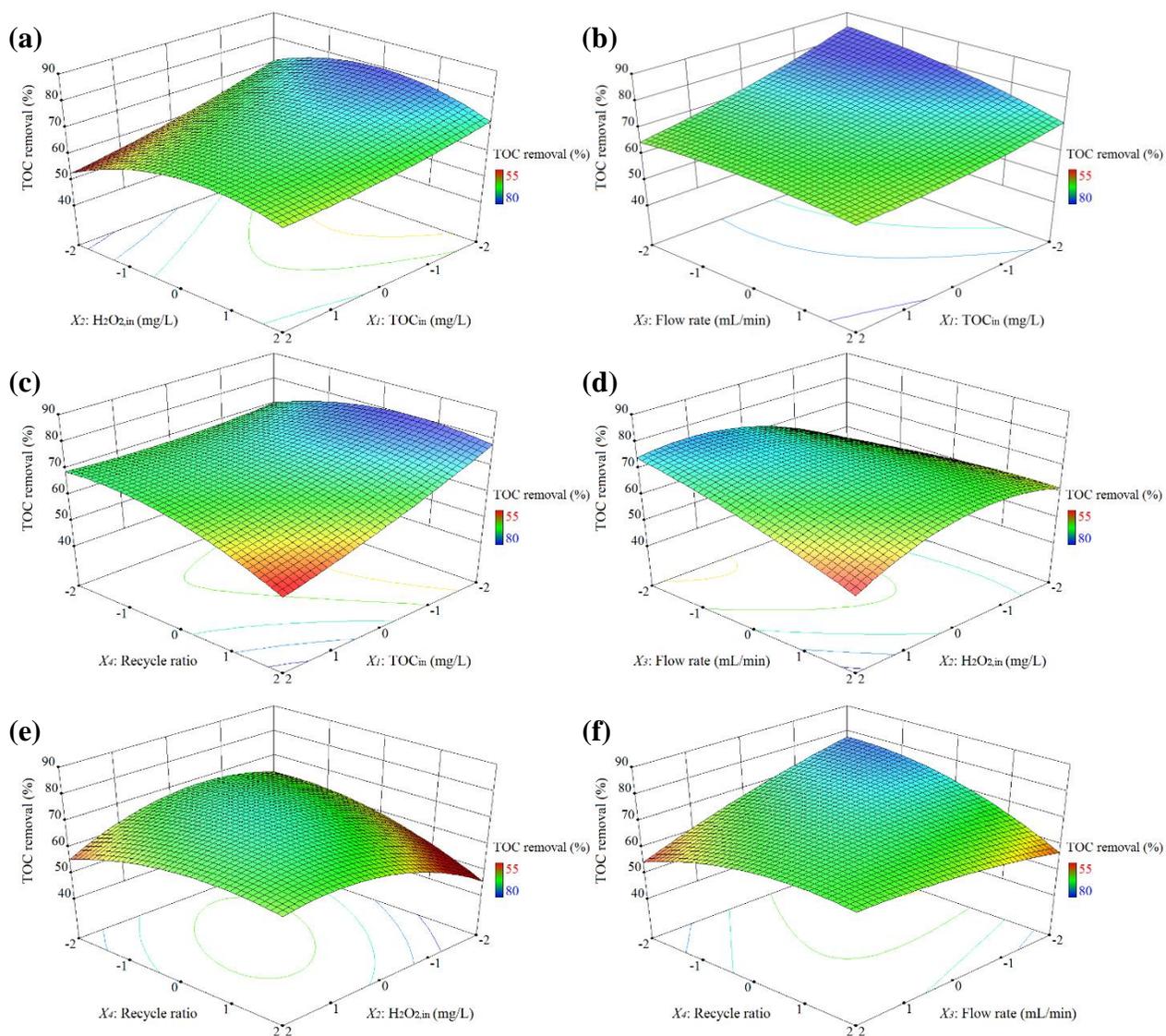


Figure 6.7. Interaction effects of different parameters on the percent TOC removal using 3D response surface and 2D contours: (a) influent concentration of TOC and H_2O_2 (X_1X_2), (b) influent concentration of TOC and flow rate (X_1X_3), (c) influent concentration of TOC and recycle ratio (X_1X_4), (d) influent H_2O_2 concentration and flow rate (X_2X_3), (e) influent H_2O_2 concentration and recycle ratio (X_2X_4), and (f) flow rate and recycle ratio (X_3X_4).

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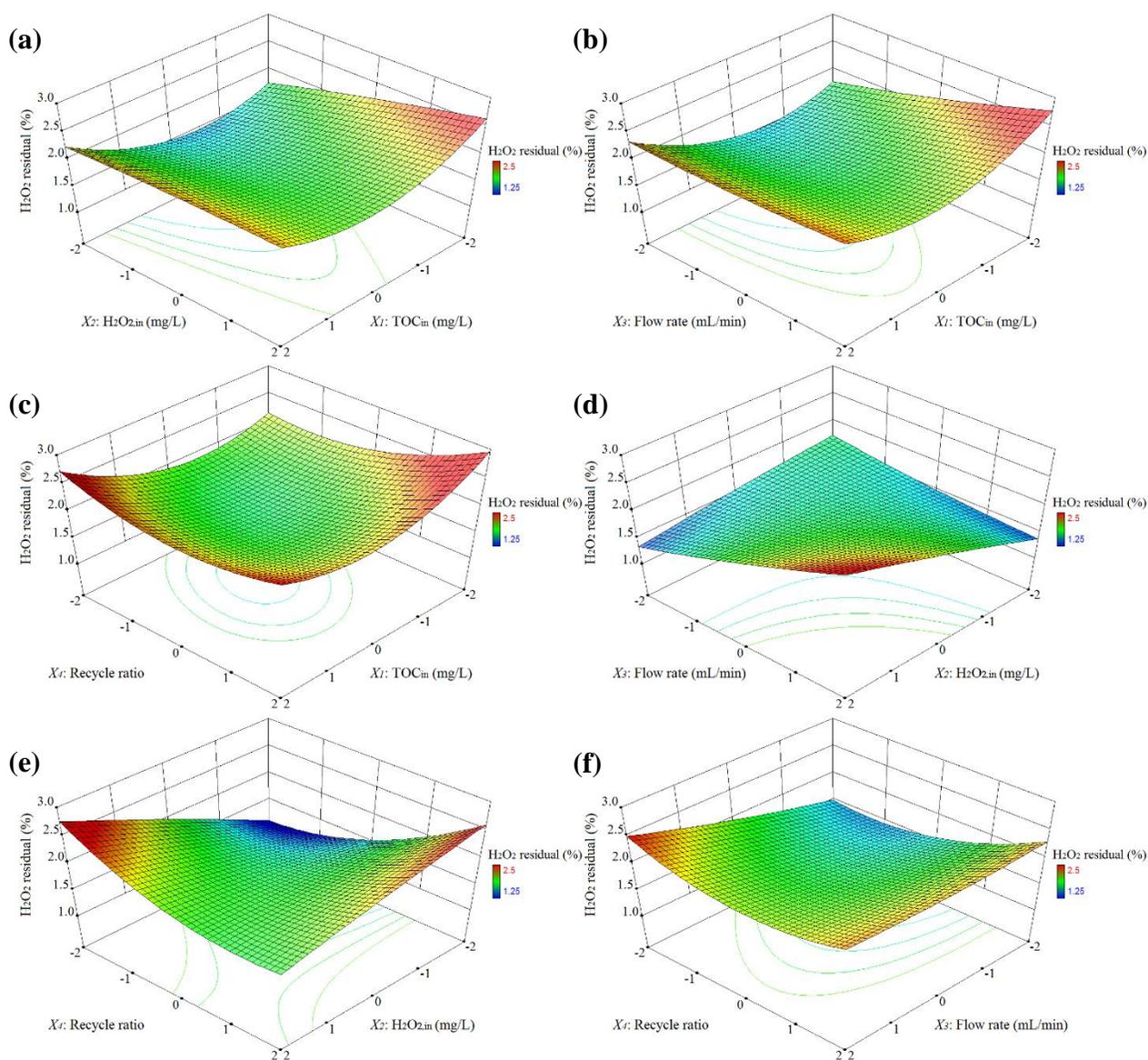


Figure 6.8. Interaction effects of different parameters on the H_2O_2 residual using 3D response surface and 2D contours: (a) influent concentration of TOC and H_2O_2 (X_1X_2), (b) influent concentration of TOC and flow rate (X_1X_3), (c) influent concentration of TOC and recycle ratio (X_1X_4), (d) influent H_2O_2 concentration and flow rate (X_2X_3), (e) influent H_2O_2 concentration and recycle ratio (X_2X_4), and (f) flow rate and recycle ratio (X_3X_4).

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On the other hand, Figures 6.7(a, d, e) depict the effects of the influent H_2O_2 concentration on the percent TOC removal. Results show that by augmenting the H_2O_2 concentration, the percent TOC removal also increases up to an optimum H_2O_2 concentration. After this point, the trend is reversed due to the excess of H_2O_2 , resulting in hydroxyl radical scavenging effect (Mehrvar et al., 2001; Bali et al., 2004; Kralik et al., 2010).

Similar results are illustrated in Figures 6.8(a–c), where the effect of the influent TOC concentration on the H_2O_2 residual is observed. In this case, by increasing the influent TOC concentration, the H_2O_2 residual is reduced up to an optimum concentration of TOC.

The interaction of the flow rate with other independent variables (X_1X_3 , X_2X_3 , and X_3X_4) tend to be linear as confirmed in Figures 6.7 and 6.8 (b, d, f). These interactions confirm that the percent TOC removal is inversely proportional to the flow rate, while the H_2O_2 residual is directly proportional to the flow rate.

Lastly, Figures 6.7 and 6.8 (c, e, f) depict the interaction effects of the recycle ratio with other variables, including the influent TOC concentration (X_1X_4), the influent H_2O_2 concentration (X_2X_4), and the flow rate (X_3X_4) on the TOC removal and the H_2O_2 residual. The cross-factor interactions of the recycle ratio had a high significant effect on both TOC removal and H_2O_2 residual. Therefore, an optimum recycle ratio was required to achieve a maximum TOC removal with a minimum H_2O_2 residual in treating SWW effluents by UV/ H_2O_2 process.

6.3.5. Optimization of operating conditions and process parameters

The RSM was used to determine the optimum experimental conditions of the four independent variables, including the influent TOC concentration (X_1), the influent H_2O_2 concentration (X_2), the flow rate (X_3), and the recycle ratio (X_4), to obtain the maximum percent TOC removal and the minimum H_2O_2 residual.

The optimization was accomplished by maximizing the percent TOC removal while minimizing the H_2O_2 residual at defined optimization conditions using the numerical optimization method built into the statistical software Design-Expert 9.0.4.1. Equations (6.4) and (6.5) were defined as objective functions for the percent TOC removal and the H_2O_2 residual, respectively, and the independent factors

in their critical range were used as constraints. The numerical optimization method explores the design space using the developed models to find the optimum factor conditions that meet the previously set goals of maximum TOC removal and minimum H₂O₂ residual simultaneously.

The multiple response approach (Equation 6.3) was used to obtain the desirability 3D response surface (Figure 6.9) by maximizing the percent removal of TOC (d_1) and minimizing the H₂O₂ residual (d_2) using the optimum factor settings. Thus, the optimum conditions to achieve the maximum TOC removal of 80.66% and minimum H₂O₂ residual of 1.35% after 120 min were found as follows: influent TOC concentration of 23.93 mg/L, influent H₂O₂ concentration of 861.54 mg/L, flow rate of 15.15 mL/min, and recycle ratio of 0.18.

The obtained optimal operating conditions were used in another experimental run to validate the predicted values. Consequently, the TOC removal of 81.03% and H₂O₂ residual of 1.29% were obtained experimentally, confirming the reliability of the model since they are both between the 95% CI of 77.46–83.84% for TOC removal and 1.26–1.59% for H₂O₂ residual.

6.4. Conclusions

Response surface methodology combined with a four-factor, five-level central composite design revealed reliable results for the treatment of slaughterhouse wastewater by UV/H₂O₂ process in a continuous photoreactor with recycle. The accuracy of the developed quadratic models was evaluated using analysis of variance. Results demonstrated that the influent concentrations of total organic carbon and H₂O₂, the flow rate, and the recycle ratio presented considerable effect on the total organic carbon removal and the H₂O₂ residual.

The interaction between influent concentrations of total organic carbon and H₂O₂ (X_1X_2) did not indicate a significant impact on the total organic carbon removal while being significant on the H₂O₂ residual. In contrast, the cross-factor interactions of the recycle ratio with other variables, including the influent concentration of total organic carbon (X_1X_4), the influent H₂O₂ concentration (X_2X_4), and the flow rate (X_3X_4), were found to have a high significant effect on both the total organic carbon removal and the H₂O₂ residual. Thus, an optimum recycle ratio was found to be highly significant to achieve a maximum total organic carbon removal with a minimum H₂O₂ residual for the treatment of slaughterhouse wastewater by UV/H₂O₂ process.

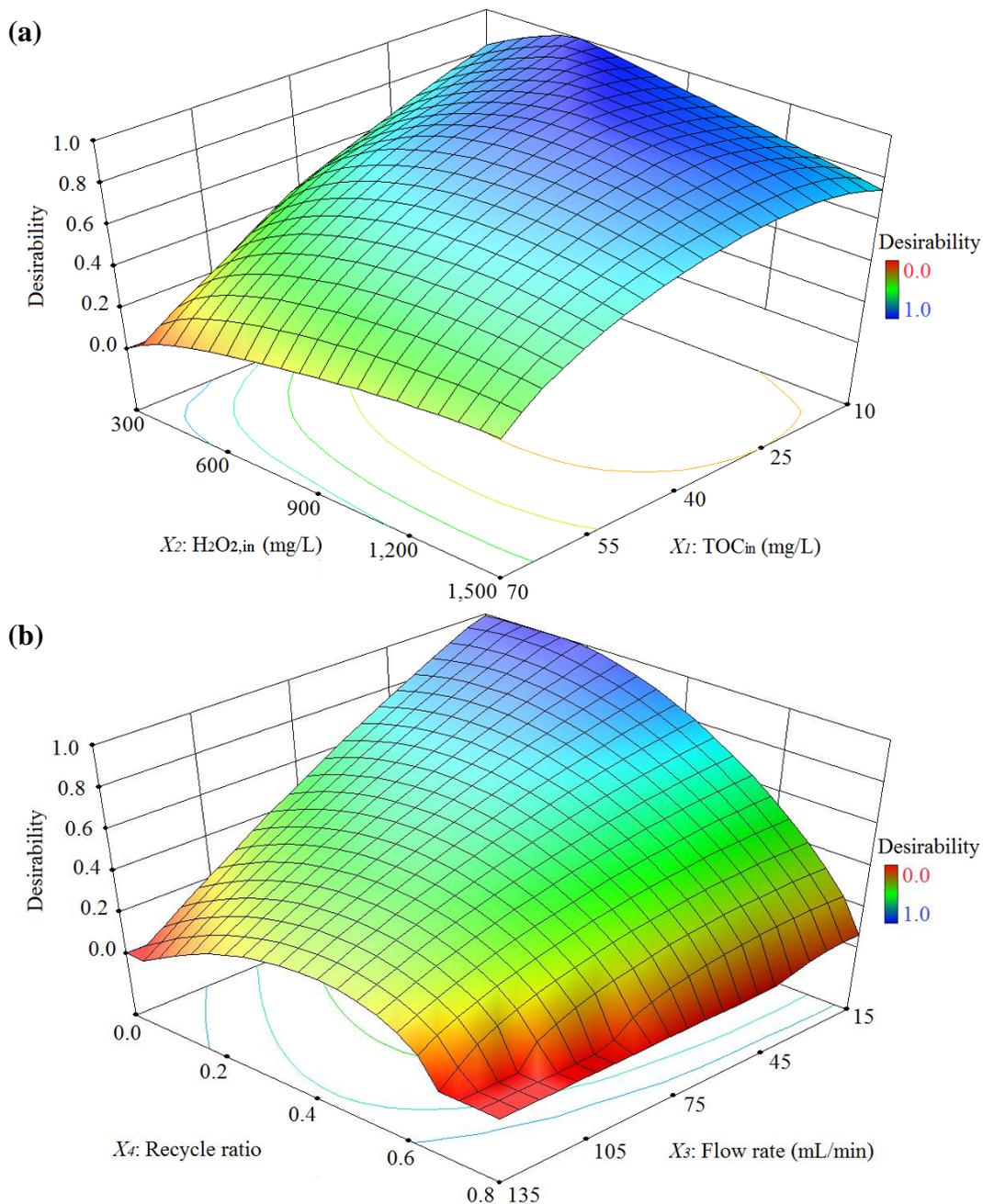


Figure 6.9. Desirability response surface, maximizing the percent removal of TOC and minimizing the H₂O₂ residual at optimum factor settings: (a) influent concentration of TOC and H₂O₂ (X_1X_2) interaction with optimum flow rate (15 mL/min) and recycle ratio (0.18); (b) flow rate and recycle ratio (X_3X_4) interaction with optimum influent TOC concentration (24 mg/L) and H₂O₂ (860 mg/L).

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A maximum total organic carbon removal of 81% and minimum H₂O₂ residual of less than 2% were found at the optimum operating conditions of 24 mg/L influent concentration of total organic carbon, 860 mg/L influent H₂O₂ concentration, 15 mL/min flow rate, and recycle ratio of 0.18 based on the developed quadratic models and the desirability multiple response method.

An additional experimental trial validated the model predictions for the maximum total organic carbon removal and minimum H₂O₂ residual at the obtained optimum operating conditions. The developed mathematical models provided a detailed exploration of the simultaneous cross-factor interactive effects of the independent variables on the responses. Therefore, the proposed models explaining the photochemical treatment of slaughterhouse wastewater by the continuous UV/H₂O₂ photoreactor with recycle could be used as a base for future studies on process optimization, photoreactor design, modeling, and scale-up. A continuous UV/H₂O₂ photoreactor with recycle could significantly increase the removal of total organic carbon while reducing the percent H₂O₂ residual in the effluent as a post-treatment method. Thus, becoming a cost-effective alternative to conventional methods and beneficial to the environment.

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CHAPTER 7

SLAUGHTERHOUSE WASTEWATER CHARACTERIZATION AND TREATMENT: AN ECONOMIC AND PUBLIC HEALTH NECESSITY OF THE MEAT PROCESSING INDUSTRY IN ONTARIO, CANADA*

Abstract

The characteristics of the slaughterhouse effluents and current wastewater treatment practices in the province of Ontario, Canada are analyzed. Meat processing plants are found to produce large amounts of wastewater due to the slaughtering process and cleaning of their facilities. Furthermore, the composition of the wastewater varies according to the type and number of animals slaughtered and the water requirements of the process. However, the slaughterhouse wastewater usually contains high levels of organics and nutrients. Several slaughterhouses in Ontario discharge their wastewater into the municipal sewer system after primary pre-treatment at the meat processing plant. Therefore, due to the high-strength characteristics of the slaughterhouse effluents, an extensive treatment for a safe discharge into the environment is required. Thus, the combination of biological processes and advanced oxidation technologies for slaughterhouse wastewater treatment are evaluated in this study. Results show that the application of combined biological and advanced oxidation processes is recommended for on-site slaughterhouse wastewater treatment.

Keywords: Slaughterhouse wastewater, anaerobic digestion, activated sludge, advanced oxidation processes.

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C. Bustillo-Lecompte, M. Mehrvar, and E. Quiñones-Bolaños (2016) Slaughterhouse wastewater characterization and treatment: an economic and public health necessity of the meat processing industry in Ontario, Canada. *Journal of Geoscience and Environment Protection* 4, pp. 175-186. Open Access. DOI: 10.4236/gep.2016.44021.

7.1. Introduction

The treatment of water and wastewater has become crucial due to the continuous growth of world population and the pollution of freshwater because of not adequately treated wastewater discharged into environment, especially in developing countries (Bustillo-Lecompte and Mehrvar, 2015). Besides, the decreasing availability of freshwater has redirected the objectives in the area of wastewater treatment to recycling and reuse.

Nevertheless, diverse techniques are adopted for water and wastewater treatment depending on the differences in geographic location, financial resources, living standards, and life quality in different countries, as well as the characteristics of the wastewater effluents and pollutants (Daigger, 2009).

The meat processing industry produces large volumes of slaughterhouse wastewater (SWW) from the slaughtering of animals and cleaning of the slaughterhouse facilities. Up to 24% of the water used in the food and beverage industry is from the meat processing (Gerbens-Leenes et al., 2013). Slaughterhouses and meat processing plants (MPPs) are part of a large industry worldwide, where the composition of the wastewater depends on the diverse practices in the slaughtering process. Consequently, SWW requires significant treatment for a safe and sustainable release to the environment (Bustillo-Lecompte and Mehrvar, 2015).

According to Mittal (2006), slaughterhouses in Ontario, Canada, typically discharge the SWW into the municipal sewer system after a preliminary treatment. Thus, slaughterhouses commonly pay surcharges, penalties, or fines to dispose their effluents into receiving municipal wastewater treatment plants.

Moreover, there are currently 134 MPPs in Ontario that can process 100-200 animals per month. Approximately 53% of Ontario's slaughterhouses do not treat their wastewater on-site before disposal. Dissolved air flotation (DAF) or aeration is the typical method of preliminary treatment with 16% of Ontario's slaughterhouses using it at their facilities. The rest of slaughterhouses (31%) use passive methods such as lagoons or storage tanks to settle solids (Figure 7.1) (Bustillo-Lecompte and Mehrvar, 2015).

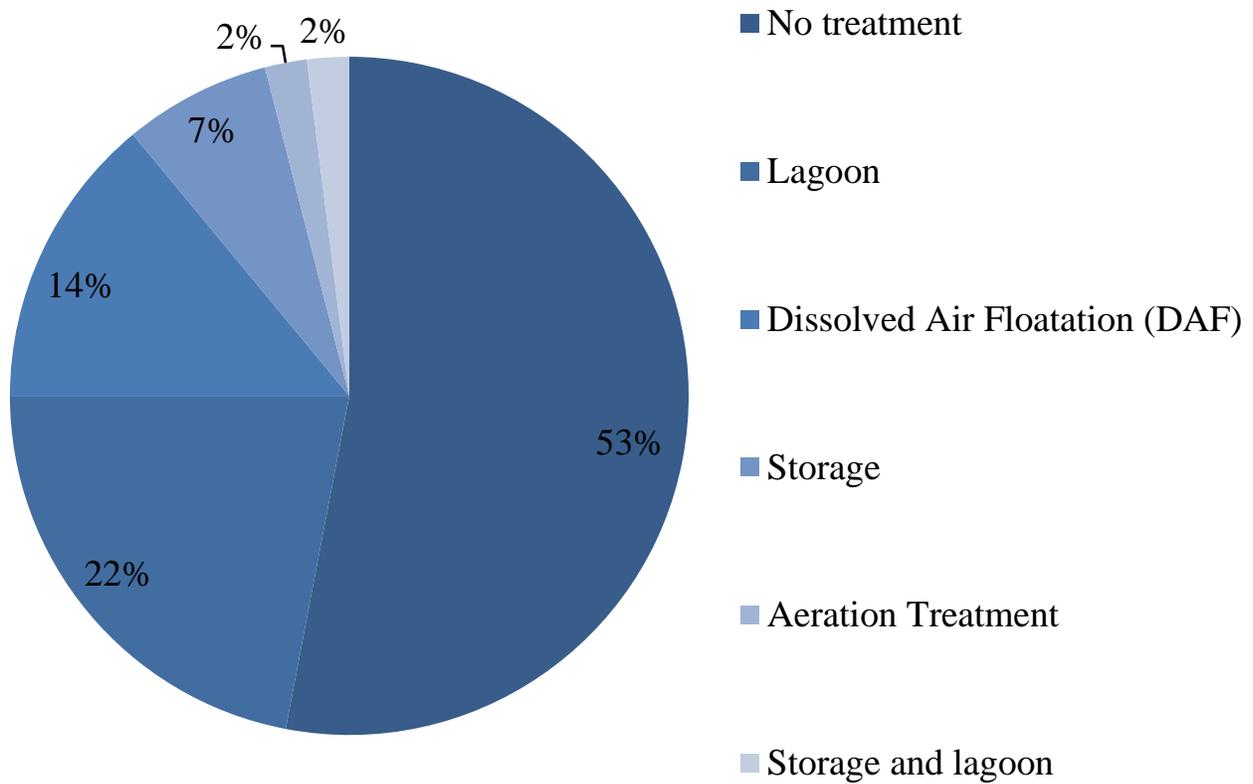


Figure 7.1. On-site slaughterhouse wastewater treatment in Ontario.

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Direct discharge of untreated slaughterhouse effluents to a water body is not practical due to the high organic load of the SWW. Therefore, appropriated disposal and treatment is required. It may be also stated that in terms of operation and economics, it is beneficial to implement combined processes for the management of slaughterhouse effluents since it couples the benefit of different technologies to improve high strength industrial wastewater treatment (Bustillo-Lecompte et al., 2014).

Advantages of the combined processes include potential energy recovery from the conversion of organic pollutants into biogas with high overall treatment efficiency (Bustillo-Lecompte et al., 2014). However, SWWs may contain toxic and non-biodegradable organic substances, which make biological treatment alone insufficient (Bustillo-Lecompte and Mehrvar, 2015). Thus, advanced oxidation processes (AOPs) are used to improve the bio-treatability of wastewaters containing non-biodegradable organics, which are toxic to common microorganisms. AOPs are becoming an attractive alternative to conventional treatment methods and a complimentary treatment option to biological processes in SWW treatment. Furthermore, AOPs can inactivate microorganisms for disinfection while avoiding the formation of hazardous by-products (Barrera et al., 2012).

This study aims to identify the characteristics of the slaughterhouse wastewater in Ontario, Canada and discuss possible treatment alternatives to minimize the impact of the discharge of these wastewaters to the environment, and to optimize processes for organics and nutrient removal, including combined biological treatment and AOPs for water reuse. Consequently, the effects of the influent concentration of TOC, flow rate, pH, H₂O₂ dosage, and their interactions on the overall treatment efficiency of the combined anaerobic-aerobic and UV/H₂O₂ process and the effluent H₂O₂ residual concentration were investigated using the design of experiments (DOE) to optimize the combined processes in continuous mode at laboratory scale for SWW treatment. Statistical models were also developed to predict the percent TOC removal and the effluent concentration of H₂O₂ as response variables. The statistical models were validated by an additional set of experiments at the optimum conditions in line with the DOE results.

7.2. Materials and methods

7.2.1. Materials

Actual SWW samples were taken from selected provincially licensed meat processing plants directly from their source in Ontario, Canada (OMAFRA, 2015b). A 30% w/w hydrogen peroxide

solution was purchased from Sigma-Aldrich, whereas NaOH (50% w/w) and H₂SO₄ (98% w/w) were obtained from EMD Millipore for pH adjustment.

7.2.2. Slaughterhouse wastewater characteristics

The main source of SWW are the feces, urine, blood, lint, fat, carcasses, and non-digested food in the intestines of the slaughtered animals, the production leftovers, and the cleaning of the facilities (Bustillo-Lecompte et al., 2013). The SWW composition varies according to the industrial process and water demand. Nevertheless, they usually contain high levels of organics and nutrients, typically measured as biochemical oxygen demand (BOD), chemical oxygen demand (COD), total organic carbon (TOC), total suspended solids (TSS), total nitrogen (TN), and phosphorus (TP).

Slaughterhouse effluents are considered detrimental worldwide due to its complex composition of fats, proteins, and fibers, as well as the presence of organics, nutrients, pathogenic and non-pathogenic microorganisms, detergents and disinfectants used for cleaning activities, and pharmaceuticals for veterinary purposes (Tritt and Schuchardt, 1992). Therefore, the treatment and disposal of wastewater from slaughterhouses and meat processing plants are an economic and public health necessity (Debik and Coskun, 2009). Table 7.1 attempts to summarize the typical characteristics of the slaughterhouse effluents in Ontario, Canada. The SWW features and common ranges are listed as BOD, COD, TOC, TSS, TN, and pH.

Table 7.1. Common characteristics of slaughterhouse wastewater in the study.

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Parameter	Range	Average
BOD (mg/L)	610–4,635	1,209
Ca (mg/L)	32–316	67
COD (mg/L)	1250–15,900	4,221
K (mg/L)	0.01–100	90
Na (mg/L)	62–833	621
Pb (mg/L)	0.21–34	4
TN (mg/L)	50–841	427
TOC (mg/L)	100–1,200	546
TP (mg/L)	25–200	50
TSS (mg/L)	300–2,800	1,164
pH	4.90–8.10	6.95

7.2.3. *Experimental setup and procedure*

An anaerobic baffled reactor (ABR), followed by an aerobic activated sludge (AS) reactor, and a UV/H₂O₂ photoreactor, operated in continuous mode, were used in a combined system at the laboratory scale for SWW treatment. The schematic diagram of the experimental setup for the combined ABR–AS–UV/H₂O₂ processes is illustrated in Figure 7.2.

The 50 L combined ABR–AS–UV/H₂O₂ system consisted of a 36-L ABR with five equal-volume chambers integrated with individual headspaces, biogas collection piping, and a 13-L aerobic AS reactor with a monitored air flow rate, and a 1-L photoreactor with recycle and uniform light distribution. A 45° slanted-edge baffle within each ABR chamber permits the down- and up-flow of the SWW, providing effective mixing and contact time between the SWW and the biomass. The AS airflow rate was set at 2 L/min to guarantee nitrifying bacteria growth and dissolved oxygen (DO) concentrations over 2.0 mg/L.

Anaerobic and aerobic sludge seeds were loaded into the anaerobic and aerobic bioreactors, respectively. The inoculum was acclimatized in two months by feeding the actual SWW continuously into the reactors at a constant flow rate (75 mL/min) while gradually increasing its concentration.

The stainless steel cylindrical photoreactor (Barrier SL-1S – Siemens Inc., Markham, ON) had an external diameter of 8 cm and a length of 34 cm with a 2.5 cm diameter UV-C lamp and output power of 6 W with 254 nm wavelength was inserted into the center of the photoreactor. A quartz sleeve covered the UV-C lamp to protect the lamp from fouling and maintain a uniform UV radiation emission.

TOC concentrations were analyzed for each sample using an automated TOC analyzer (Teledyne Tekmar Apollo 9000, Mason, OH). Temperature and pH were measured daily using a pH meter with a temperature probe (Thermo Scientific Orion 230A+, Ottawa, ON). The H₂O₂ residuals were measured with a UV-Visible Spectrophotometer (Ultrospec 1100 pro – Amersham Biosciences, Amersham, UK) at 454 nm using neocuproine and copper (Bustillo-Lecompte et al., 2016a). All experiments were repeated in triplicates, and the average values were reported. Furthermore, three replicates were made for each analytical measurement.

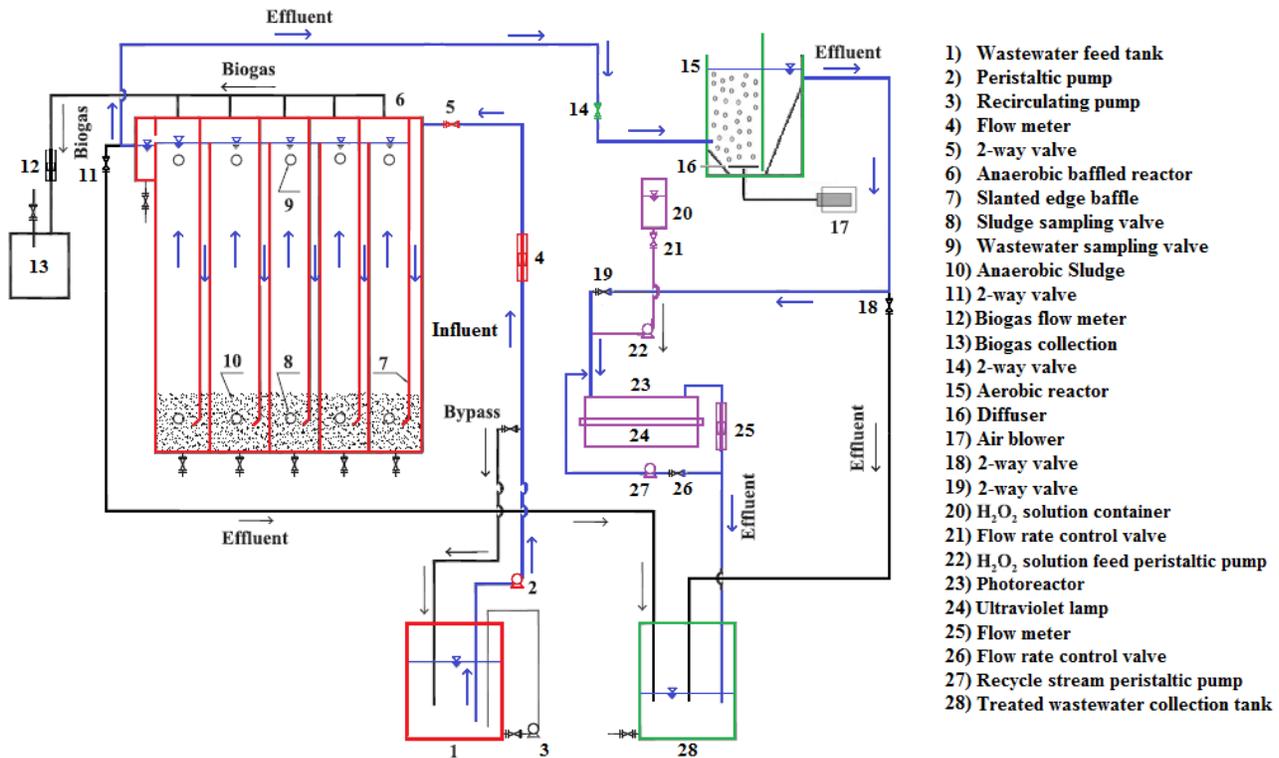


Figure 7.2. Schematic diagram of the combined anaerobic, aerobic, and UV/H₂O₂ processes for the treatment of SWW.

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7.2.4. Experimental design and optimization

A four-factor along with five-level CCD in conjunction with RSM was used to maximize percent TOC removal and minimize percent H₂O₂ residuals in the effluent. The influent concentration of TOC (X_1), flow rate (X_2), H₂O₂ dosage (X_3), and pH (X_4) were used as independent factors in the DOE; whereas, the percent TOC removal (Y_1) and H₂O₂ residual (Y_2) were considered process responses. Thus, each factor was coded at five levels, from -2 to +2, as shown in Table 7.2. Previous studies (Bustillo-Lecompte and Mehrvar, 2015; OMAFRA, 2015b; Bustillo-Lecompte et al., 2015, 2016a) were used to determine and select the critical ranges of the factors.

Table 7.2. Independent variables with coded levels based on a four-factor, five level CCD.

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Independent variable	Symbol	Coded levels				
		-2	-1	0	1	2
TOC _{in} (mg/L)	X_1	50	450	850	1,250	1,650
Flow rate (mL/min)	X_2	15	45	75	105	135
H ₂ O ₂ in (mg/L)	X_3	100	300	500	700	900
pH	X_4	3	5	7	9	11

Equation (7.1) was used to predict the model responses as a quadratic model and estimate the parametrical coefficients by correlating dependent and independent variables using the least-squares regression (Bustillo-Lecompte et al., 2016a):

$$Y = \beta_o + \sum_{i=1}^k \beta_i X_i + \sum_{i=1}^k \beta_{ii} X_i^2 + \sum_{i=1}^{k-1} \sum_{j=2}^k \beta_{ij} X_i X_j + c \quad (7.1)$$

where β_o , β_i , β_{ii} , and β_{ij} are the constant, linear, quadratic, and cross-factor interaction coefficients, respectively; X_i and X_j represent the independent variables; Y_i is the predicted response; and c and k are the residual term and the number of factors, respectively.

The Design-Expert 9.0.4.1 statistical software was employed for graphical and regression analysis to estimate the coefficients of the response functions. The significance of the independent variables, factor interactions, and model equations were examined by analysis of variance (ANOVA) at 95% confidence intervals (CI). Three-dimensional (3D) surfaces and two-dimensional (2D) contour plots were obtained while keeping another factor constant in the quadratic models. Experiments were carried

out to validate the statistical models for maximum percent TOC removal and minimum H₂O₂ residual. Optimal operating conditions were estimated using the numerical optimization method built in the software. Lastly, an additional experimental run was carried out to validate the predicted optimal conditions for both response functions, the percent removal of TOC, and H₂O₂ residual. The desirability multiple response method was used to combine the desirable ranges for each response to obtaining a simultaneous objective function that represents the geometric mean of all transformed responses as shown in Equation (7.2) (Myers et al., 2004):

$$D = (d_1 \times d_2 \times \dots \times d_n)^{1/n} = \left(\prod_{i=1}^n d_i \right)^{1/n} \quad (7.2)$$

where D , d_i , and n are the desirability objective function, each response range, and the number of responses, respectively. If any of the analyzed responses is found to be outside of their desirability range, the overall desirability function becomes zero. Therefore, for a simultaneous optimization, each response is required to be assigned low and high values for optimization. In this case, the percent removal of TOC (d_1) is maximized while the H₂O₂ residual (d_2) is minimized.

7.3. Results and discussion

7.3.1. Experimental design and statistical analysis

Table 7.3 portrays the four-factor, five-level CCD with observed and predicted values for both percent TOC removal and H₂O₂ residual by the developed quadratic models related to the combined ABR–AS–UV/H₂O₂ system in a continuous photoreactor for SWW treatment. RSM was employed for parameter estimation, indicating the relationship between the input factors and the responses, as shown in Equation (7.2). Thus, to predict the response functions for percent TOC removal and H₂O₂ residual, the second-order polynomial Equations (7.3) and (7.4) were developed, respectively:

$$Y_1 = 86.67 - 4.96X_1 - 0.59X_2 - 0.91X_3 - 1.82X_4 - 0.47X_1X_2 - 1.26X_1X_3 - 0.31X_1X_4 + 0.82X_2X_3 + 0.33X_2X_4 - 3.17X_3X_4 + 0.93X_1^2 - 0.02X_2^2 - 1.06X_3^2 - 1.88X_4^2 \quad (7.3)$$

$$Y_2 = 1.75 - 0.01X_1 + 0.17X_2 + 0.09X_3 + 0.05X_4 - 0.02X_1X_2 - 0.03X_1X_3 - 0.09X_1X_4 - 0.02X_2X_3 + 0.09X_2X_4 + 0.04X_3X_4 + 0.05X_1^2 - 0.01X_2^2 + 0.03X_3^2 + 0.04X_4^2 \quad (7.4)$$

Table 7.3. Four-factor, five-level CCD with observed and predicted percent TOC removal and H₂O₂ residual.

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Run	Independent coded variables				TOC removal (%)		H ₂ O ₂ residual (%)	
	X ₁	X ₂	X ₃	X ₄	Observed	Predicted	Observed	Predicted
1	450	45	300	5	88.74	88.85	1.51	1.53
2	1,250	45	300	5	83.11	83.01	1.78	1.78
3	450	105	300	5	86.64	86.33	1.74	1.77
4	1,250	105	300	5	78.42	78.60	1.92	1.94
5	450	45	700	5	94.16	94.26	1.72	1.74
6	1,250	45	700	5	83.29	83.37	1.84	1.87
7	450	105	700	5	95.51	95.01	1.91	1.91
8	1,250	105	700	5	82.58	82.24	1.93	1.95
9	450	45	300	9	91.32	91.53	1.56	1.55
10	1,250	45	300	9	84.25	84.46	1.42	1.46
11	450	105	300	9	90.68	90.31	2.14	2.15
12	1,250	105	300	9	81.58	81.35	1.98	1.97
13	450	45	700	9	84.72	84.25	1.9	1.92
14	1,250	45	700	9	71.97	72.14	1.71	1.69
15	450	105	700	9	86.34	86.30	2.42	2.44
16	1,250	105	700	9	72.71	72.31	2.11	2.13
17	50	75	500	7	99.89	100.0	2.01	1.98
18	1,650	75	500	7	80.48	80.48	1.95	1.93
19	850	15	500	7	88.15	87.78	1.39	1.37
20	850	135	500	7	84.63	85.42	2.08	2.05
21	850	75	100	7	84.31	84.24	1.71	1.69
22	850	75	900	7	80.11	80.60	2.09	2.06
23	850	75	500	3	82.62	82.79	1.84	1.80
24	850	75	500	11	75.28	75.53	2.01	2.00
25	850	75	500	7	86.85	86.67	1.73	1.75
26	850	75	500	7	85.95	86.67	1.73	1.75
27	850	75	500	7	86.81	86.67	1.75	1.75
28	850	75	500	7	86.30	86.67	1.76	1.75
29	850	75	500	7	87.53	86.67	1.78	1.75
30	850	75	500	7	86.60	86.67	1.75	1.75

Negative coefficients for the model components X_1 , X_2 , X_3 , X_4 , X_1X_2 , X_1X_3 , X_1X_4 , X_3X_4 , X_2^2 , X_3^2 , and X_4^2 in Y_1 and X_1 , X_1X_2 , X_1X_3 , X_1X_4 , X_2X_3 , and X_2^2 in Y_2 , indicate unfavorable effects on the percent TOC removal and the H_2O_2 residual, respectively. Whereas, positive coefficients for X_2X_3 , X_2X_4 , and X_1^2 in Y_1 and X_2 , X_3 , X_4 , X_2X_4 , X_3X_4 , X_1^2 , X_3^2 , and X_4^2 in Y_2 indicate favorable effects on the percent TOC removal and the H_2O_2 residual, respectively. Since the coefficients with values close to zero represent lower relative intensity, X_2^2 do not intensely affect the TOC removal while X_1 , X_1X_2 , X_2X_3 , and X_2^2 do not intensely affect H_2O_2 residual.

Although this evaluation provides a rapid analysis of the parametrical effect on the response variables, ANOVA with 95% CI was also applied to evaluate the statistical significance of the developed quadratic models for the percent TOC removal and the H_2O_2 residual. Thus, the statistical significance of each factor coefficient, as shown in Equations (7.3) and (7.4), was determined by the Fisher's (F) exact test, comparing probability (p) values greater than F . Consequently, the model F -values of 287.69 and 116.90 for TOC removal and H_2O_2 residual, respectively, imply the models are significant.

Besides, small probability values ($p < 0.05$) indicate significant model terms, which confirm the accuracy of the developed models to predict the response functions. Conversely, p -values > 0.10 indicate the model terms are not significant; in this case, X_2^2 is not significant for both TOC removal and H_2O_2 residual. If the quadratic effect is not significant, then the optimal levels of the parameter are in the extremes of the experimental region (Botha et al., 2012).

The goodness of fit of the developed models was validated by the determination coefficient (R^2) and the adjusted R^2 that ensures an adequate variation of the quadratic model to the experimental values. The values of R^2 and adjusted R^2 were found to be 0.9963 and 0.9928 for the percent TOC removal and 0.9909 and 0.9824 for the H_2O_2 residual, respectively, representing an adequate model significance. Moreover, the adequate precision for the percent TOC removal and H_2O_2 residual models were found to be 77.49 and 51.54, respectively (Table 7.4). Since both values were greater than 4.00, the model can be used to navigate the CCD design space (Ghafoori et al., 2012). The lack of fit was calculated to assess how well the model fits the data. The lack of fit p -values of the percent TOC removal and the H_2O_2 residual were found to be 0.6059 and 0.1145, respectively. A not significant lack of fit ($p > 0.10$) indicates that the model fits the data well.

Table 7.4. ANOVA of the prediction results for the percent TOC and H₂O₂ residual by quadratic modeling.

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Source	Sum of squares	df ^a	Mean square	F value ^b	p-value (Prob. > F) ^c	Remark
TOC _{removal} model	1064.8	14	76.057	287.69	<0.0001	Significant
X ₁	590.24	1	590.24	2232.6	<0.0001	Significant
X ₂	8.3308	1	8.3308	31.512	<0.0001	Significant
X ₃	19.911	1	19.911	75.313	<0.0001	Significant
X ₄	79.061	1	79.061	299.05	<0.0001	Significant
X ₁ X ₂	3.5721	1	3.5721	13.512	0.0022	Significant
X ₁ X ₃	25.402	1	25.402	96.083	<0.0001	Significant
X ₁ X ₄	1.5006	1	1.5006	5.6762	0.0309	Significant
X ₂ X ₃	10.726	1	10.726	40.57	<0.0001	Significant
X ₂ X ₄	1.69	1	1.69	6.3925	0.0232	Significant
X ₃ X ₄	160.78	1	160.78	608.17	<0.0001	Significant
X ₁ ²	23.766	1	23.766	89.894	<0.0001	Significant
X ₂ ²	0.0088	1	0.0088	0.0333	0.8576	Not significant
X ₃ ²	30.989	1	30.989	117.22	<0.0001	Significant
X ₄ ²	96.729	1	96.729	365.88	<0.0001	Significant
Residual	3.9656	15	0.2644			
Lack of Fit	2.5139	10	0.2514	0.86581	0.6059	Not significant
Pure error	1.4517	5	0.2903			
Corrected total SS ^d	1068.8	29				
R ²	0.9963					
Adjusted R ²	0.9928					
Adequate Precision	77.489					
H ₂ O ₂ _{residual} model	1.3975	14	0.0998	116.9	<0.0001	Significant
X ₁	0.0045	1	0.0045	5.3139	0.0359	Significant
X ₂	0.697	1	0.697	816.27	<0.0001	Significant
X ₃	0.2109	1	0.2109	247.03	<0.0001	Significant
X ₄	0.063	1	0.063	73.824	<0.0001	Significant
X ₁ X ₂	0.0068	1	0.0068	7.9709	0.0128	Significant
X ₁ X ₃	0.0163	1	0.0163	19.038	0.0006	Significant
X ₁ X ₄	0.1208	1	0.1208	141.42	<0.0001	Significant
X ₂ X ₃	0.006	1	0.006	7.034	0.0181	Significant
X ₂ X ₄	0.1243	1	0.1243	145.52	<0.0001	Significant
X ₃ X ₄	0.0218	1	0.0218	25.479	0.0001	Significant
X ₁ ²	0.0729	1	0.0729	85.402	<0.0001	Significant
X ₂ ²	0.0026	1	0.0026	3.0146	0.103	Not significant
X ₃ ²	0.0273	1	0.0273	32	<0.0001	Significant
X ₄ ²	0.0392	1	0.0392	45.927	<0.0001	Significant
Residual	0.0128	15	0.0009			
Lack of Fit	0.011	10	0.0011	3.0579	0.1145	Not significant
Pure error	0.0018	5	0.0004			
Corrected total SS ^d	1.4103	29				
R ²	0.9909					
Adjusted R ²	0.9824					
Adequate Precision	51.542					

a. Degrees of freedom (*df*)

b. Fisher's (*F*) exact test value.

c. A probability value (*p*) < 0.05 is considered significant, a *p*-value > 0.10 is considered not significant.

d. Total sum of squares corrected for the mean.

On the other hand, the assumption of the constant variance was verified by plotting the internally studentized residual versus predicted values (Figures 7.3a and 7.3b). The studentized residuals were found dividing the residuals by their standard deviations showing a randomly scattered pattern within the outlier detection limits -3 and $+3$. Therefore, model predictions, described in Equations (7.3) and (7.4), for both the percent TOC removal and the H_2O_2 residual, respectively, are satisfactory.

Moreover, the normal probability plot of residuals, shown in Figures 7.4a and 7.4b for the TOC removal and the H_2O_2 residual, respectively, showed a straight-line pattern followed by the points on the plot, not an S-shaped curve. Consequently, a transformation of the response is not required because of the normal distribution of the residuals (Bustillo-Lecompte et al., 2016a).

The correlation between the observed and predicted values is shown in Figures 7.5a and 7.5b for the TOC removal and the H_2O_2 residual, respectively. As a result, minor discrepancies are represented by a straight-line trend, which indicates a good agreement between observed and predicted values. Hence, the quadratic model predictions for both percent TOC removal and H_2O_2 residual responses are satisfactory.

7.3.2. Individual and cross-factor interaction effects of model parameters

The significance of each model factor was also evaluated using the F -exact test and p -values for each factor including linear, quadratic, and cross-factor interaction. All four independent variables including influent TOC (X_1), flow rate (X_2), H_2O_2 dosage (X_3), and pH (X_4) have a significant effect on both responses since their p -values are lower than 0.05.

Besides, the cross-factor interactions of all model parameters, including the influent TOC concentration and flow rate (X_1X_2), influent TOC concentration and H_2O_2 dosage (X_1X_3), influent TOC concentration and pH (X_1X_4), flow rate and H_2O_2 dosage (X_2X_3), flow rate and pH (X_2X_4), and H_2O_2 dosage and pH (X_3X_4) showed a significant effect on both TOC removal and H_2O_2 residual. The cross-factor interaction effects with the highest significance as per their p -values < 0.0001 are illustrated in Figure 7.6.

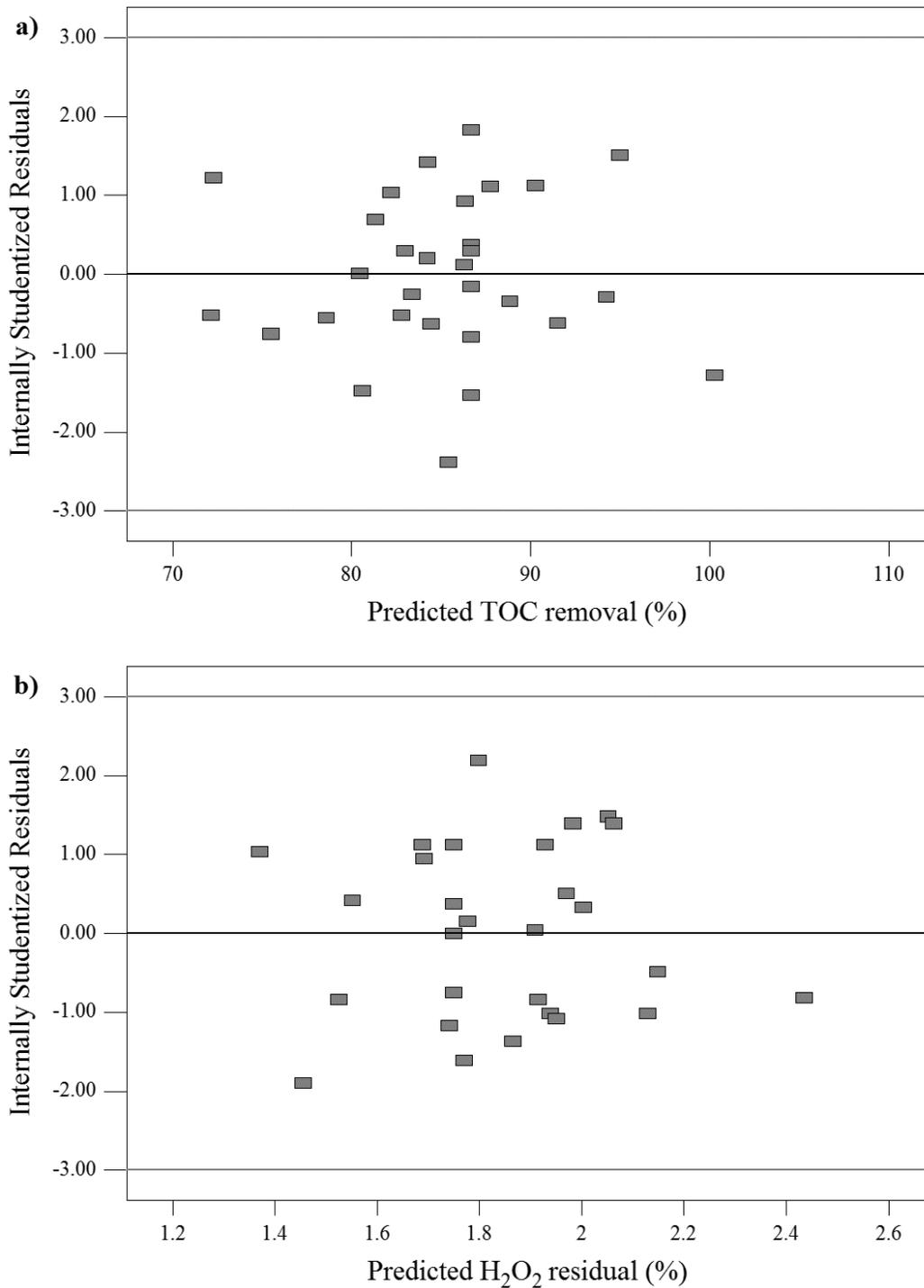


Figure 7.3. Internally studentized residuals versus predicted values for (a) percent TOC removal and (b) H₂O₂ residual.

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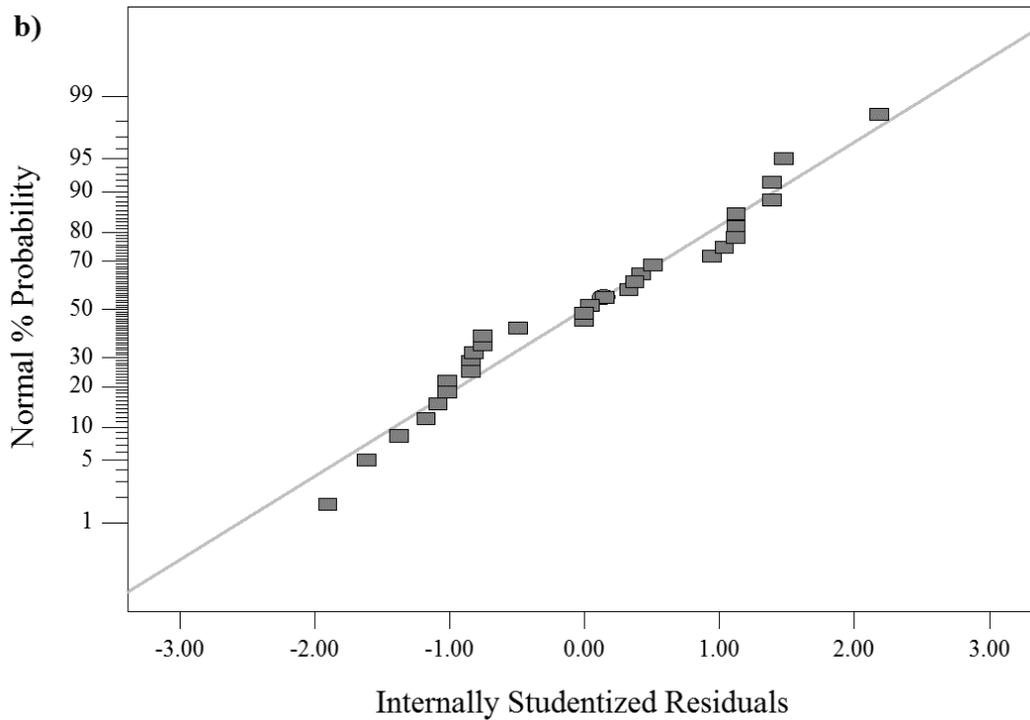
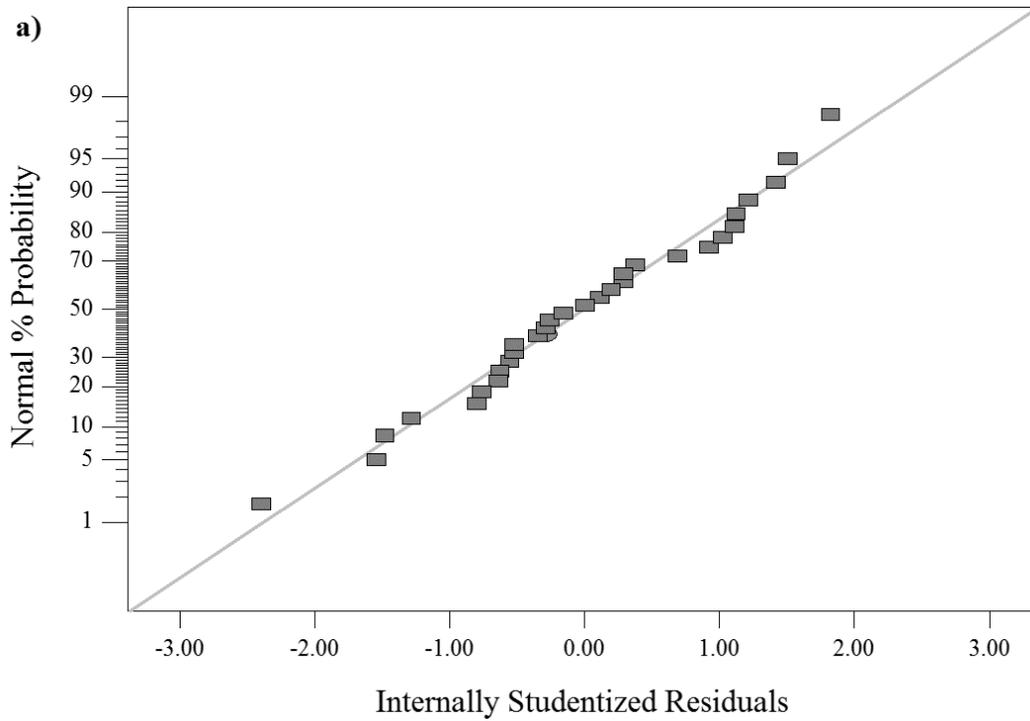


Figure 7.4. Internally studentized residuals versus normal probability for (a) percent TOC removal and (b) H₂O₂ residual.

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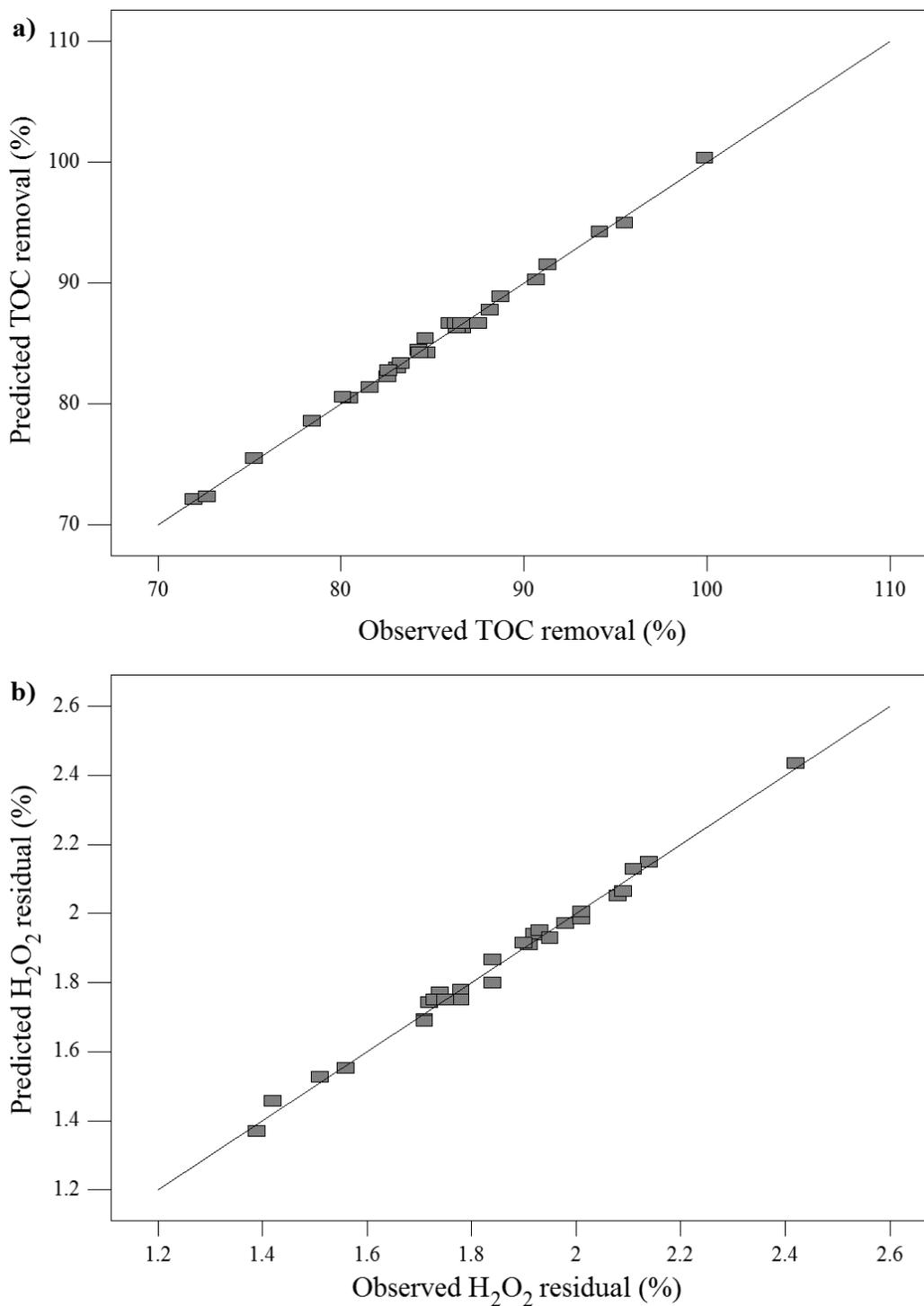


Figure 7.5. Observed experimental data versus predicted values for (a) percent TOC removal and (b) H₂O₂ residual.

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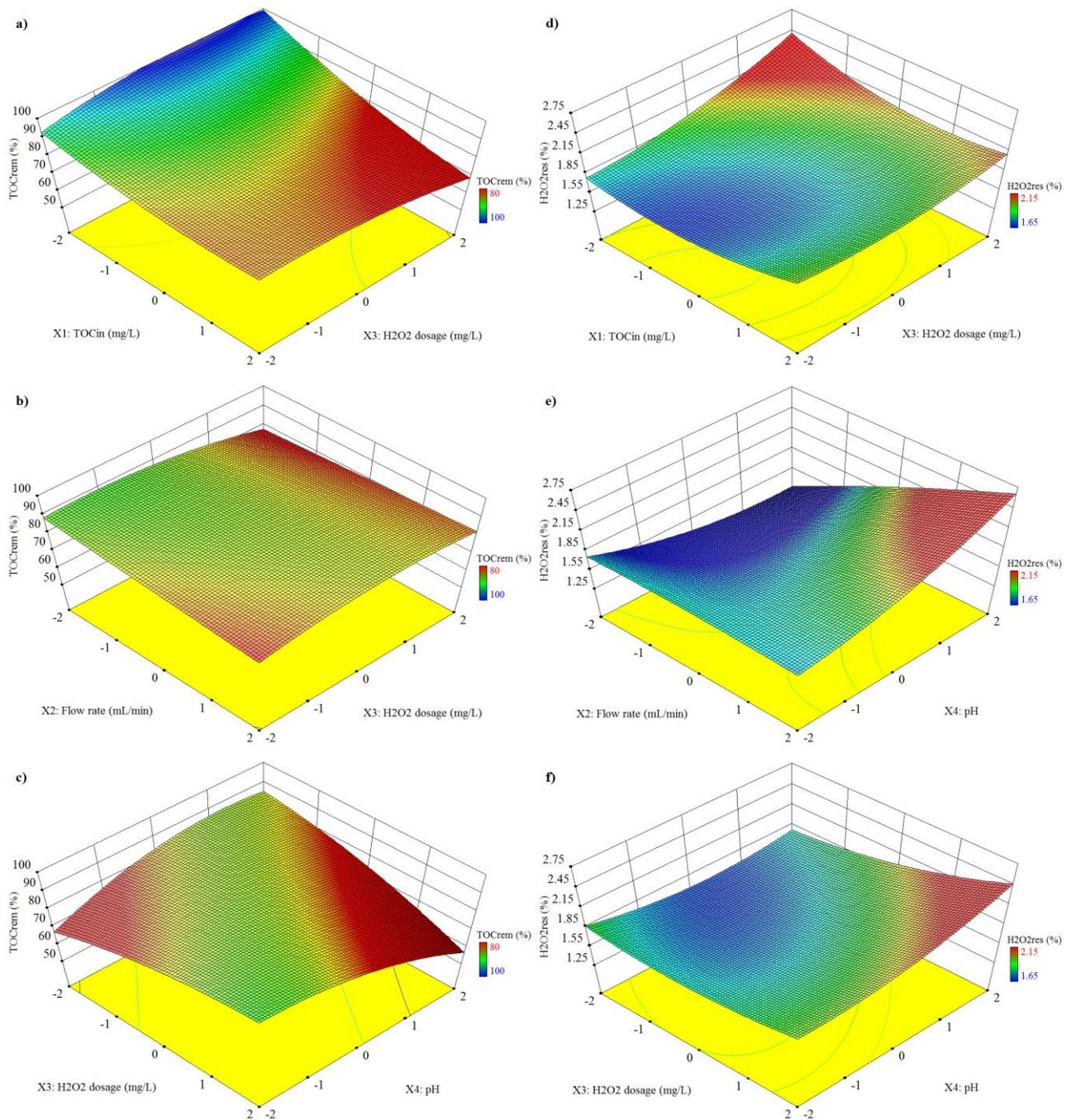


Figure 7.6. 3D surfaces and 2D plots of the interaction effects of: (a) influent TOC concentration and H₂O₂ dosage (X_1X_3), flow rate and H₂O₂ dosage (X_2X_3), and H₂O₂ dosage and pH (X_3X_4) on the TOC removal; and (d) influent TOC concentration and H₂O₂ dosage (X_1X_3), (e) flow rate and pH (X_2X_4), and (f) H₂O₂ dosage and pH (X_3X_4) on H₂O₂ residual.

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7.3.3. Optimization of operating conditions

The RSM was used to calculate the optimum conditions for the four independent variables to get maximum percent TOC removal and minimum H₂O₂ residual. Equations (3) and (4) were defined as objective functions for percent TOC removal and H₂O₂ residual, respectively, and the independent factors in their range were used as model constraints. Thus, the following optimum conditions to reach a maximum TOC removal of 98.9% and minimum H₂O₂ residual of 1.4% were found: influent TOC of 50 mg/L, flow rate of 15 mL/min, H₂O₂ dosage of 344 mg/L, and pH of 7.2. The obtained optimal operating conditions were used in an additional run to validate the predicted values. Obtaining a TOC removal of 97.8% and H₂O₂ residual of 1.3% were obtained experimentally, confirming the reliability of the model since the values are within the 95% CI.

7.4. Conclusions

The interaction effects of the influent TOC concentration, flow rate, H₂O₂ dosage, and pH had a significant effect on both TOC removal and H₂O₂ residual. Optimum conditions were found for each variable to achieve maximum TOC removal with minimum H₂O₂ residual. The developed mathematical models provided a comprehensive exploration of the cross-factor interactive effects of the independent variables on the responses. The proposed models explaining the treatment of SWW by the continuous ABR–AS–UV/H₂O₂ system were found suitable for future studies on reactor design, modeling, and scale-up.

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CHAPTER 8

TREATMENT OF AN ACTUAL SLAUGHTERHOUSE WASTEWATER BY INTEGRATION OF BIOLOGICAL AND ADVANCED OXIDATION PROCESSES: MODELING, OPTIMIZATION, AND COST-EFFECTIVENESS ANALYSIS*

Abstract

Biological and advanced oxidation processes are combined to treat an actual slaughterhouse wastewater (SWW) by a sequence of an anaerobic baffled reactor, an aerobic activated sludge reactor, and a UV/H₂O₂ photoreactor with recycle in continuous mode at laboratory scale. In the first part of this study, quadratic modeling along with response surface methodology are used for the statistical analysis and optimization of the combined process. The effects of the influent total organic carbon (TOC) concentration, the flow rate, the pH, the inlet H₂O₂ concentration, and their interaction on the overall treatment efficiency, CH₄ yield, and H₂O₂ residual in the effluent of the photoreactor are investigated. The models are validated at different operating conditions using experimental data. Maximum TOC and total nitrogen (TN) removals of 91.29 and 86.05%, respectively, maximum CH₄ yield of 55.72%, and minimum H₂O₂ residual of 1.45% in the photoreactor effluent were found at optimal operating conditions. In the second part of this study, continuous distribution kinetics is applied to establish a mathematical model for the degradation of SWW as a function of time. The agreement between model predictions and experimental values indicates that the proposed model could describe the performance of the combined anaerobic–aerobic–UV/H₂O₂ processes for the treatment of SWW. In the final part of the study, the optimized combined anaerobic–aerobic–UV/H₂O₂ processes with recycle were evaluated using a cost-effectiveness analysis to minimize the retention time, the electrical energy consumption, and the overall incurred treatment costs required for the efficient treatment of slaughterhouse wastewater effluents.

Keywords: Slaughterhouse wastewater, anaerobic digestion, activated sludge, advanced oxidation processes, process optimization.

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C. Bustillo-Lecompte and M. Mehrvar (2016) Treatment of an actual slaughterhouse wastewater by integration of biological and advanced oxidation processes: modeling, optimization, and cost-effectiveness analysis. *Journal of Environmental Management*. (In Press).

8.1. Introduction

Slaughterhouse wastewater (SWW) effluents are becoming one of the major agribusiness concerns because of the elevated amounts of water used during slaughtering, processing, and cleaning of the abattoir facilities. Although physical, chemical, and biological treatment can be used for SWW degradation, each treatment process has different benefits and drawbacks depending on the SWW characteristics, best available technology, jurisdictions, and regulations (Tabrizi and Mehrvar, 2004; Barrera et al., 2012; Franke-Whittle and Insam, 2013; Bustillo-Lecompte and Mehrvar, 2015; Valta et al., 2015; Bustillo-Lecompte et al., 2015, 2016a, 2016b). However, adopting combined processes for SWW treatment is considered operationally and economically advantageous because it incorporates and optimizes the advantages of different technologies to achieve high-quality effluents from industrial and high-strength wastewaters (Kurian et al., 2006; Mehrvar and Tabrizi, 2006; De Nardi et al., 2011; Bustillo-Lecompte et al., 2013, 2014; Bustillo-Lecompte and Mehrvar, 2015; Mowla et al., 2014).

Anaerobic treatment is the preferred biological treatment because of its effectiveness in treating high-strength wastewater such as SWW with less complex equipment requirements. Nevertheless, anaerobically treated effluents of SWW require post-treatment to comply with required discharge limits (Cao and Mehrvar, 2011; Bustillo-Lecompte et al., 2013, 2014). Therefore, aerobic treatment systems are more frequently used in wastewater treatment since they operate at higher rates than conventional anaerobic treatment methods in the case of lower strength wastewaters. Taking into account that oxygen requirements and treatment time are directly proportional to an increase in wastewater strength, the aerobic treatment are commonly used for further treatment and nutrient removal following physicochemical and anaerobic treatment methods (Bustillo-Lecompte and Mehrvar, 2015).

Furthermore, the SWW may contain toxic and non-biodegradable organic substances, making biological treatment alone insufficient. Thus, advanced oxidation processes (AOPs) are used to improve the biodegradability of wastewaters containing non-biodegradable organics and inactivate both pathogenic and non-pathogenic microorganisms without adding additional chemicals to the SWW, avoiding the formation of hazardous by-products. Consequently, AOPs are an attractive alternative to conventional treatment systems and a complementary treatment method to biological processes for the treatment of slaughterhouse effluents (Oller et al., 2011; Barrera et al., 2012; Bustillo-Lecompte and Mehrvar, 2015; Bustillo-Lecompte et al., 2016a, 2016b).

As a result, considering the eventual reduction in operation and maintenance costs, high removal efficiency requirements, potential energy recovery from biogas production, and enhanced quality for water reuse purposes, combined biological processes and AOP systems are recommended for the SWW treatment if the system were optimized at an appropriate residence time in each reactor. (Tabrizi and Mehrvar, 2004; Oller et al., 2011; Bustillo-Lecompte and Mehrvar, 2015).

Combined processes for wastewater treatment are multifactor systems due to the interactions of different parameters on the overall process efficiency including the concentration of organic matter, the reaction time, the pH, the light source intensity, the oxidant concentration, and the output power, among others, which have not been widely evaluated. Therefore, the optimization of such systems requires the consideration of both single-factor and cross-factor effects through a design of experiments (DOE) to identify the factors that influence the multivariable system while overcoming the limitations of traditional experimental methods in terms of the number of experimental trials, time, and materials. (Ghafoori et al., 2012, 2014a, 2015; Bustillo-Lecompte et al., 2016a, 2016b). On the other hand, the available information on the reaction mechanisms and detailed kinetic modeling of combined biological and AOP systems involving all free radicals and molecular species for the degradation of SWW is limited (Ghafoori et al., 2012; Bustillo-Lecompte and Mehrvar, 2015).

In this study, the effects of the influent concentration of TOC, the flow rate, the pH, the inlet concentration of H_2O_2 to the photoreactor, and their interactions on the overall efficiency of the anaerobic–aerobic–UV/ H_2O_2 processes, the effluent H_2O_2 residual concentration at the photoreactor outlet, and the CH_4 yield for the treatment of SWW were investigated. The DOE was used to optimize the SWW treatment using a combined system of an anaerobic baffled reactor (ABR), followed by an aerobic activated sludge (AS) reactor, and a UV/ H_2O_2 photoreactor with recycle in continuous mode at laboratory scale. The CH_4 yield and the removal of the TOC and the TN were maximized while minimizing the H_2O_2 residual in the effluent of the photoreactor. The optimal parametric values from the DOE were obtained using a central composite design (CCD) with four factors at five levels combined with the response surface methodology (RSM). Statistical models were also developed to predict the percentual TOC and TN removals, the effluent concentration of H_2O_2 , and CH_4 yield as response variables by the combined anaerobic–aerobic-UV/ H_2O_2 processes. The statistical models were validated by an additional set of experiments at the optimum conditions in line with the DOE results.

In the second part of this study, the reactors in the combined processes were analyzed to find the degradation models for the prediction of the percentual TOC removal as the output variable as a function of time. The degradation models were validated by another set of experimental data carried out under the optimized operating conditions based on the results of the experimental design. Finally, the optimized combined ABR–AS–UV/H₂O₂ system with recycle was evaluated using a cost-effectiveness analysis (CEA), minimizing the incurred treatment costs, the electrical energy consumption, and the retention time required for the efficient treatment of slaughterhouse effluents. The results from this study contribute towards the cost-effective use of combined biological and advanced oxidation processes for the treatment of actual wastewater from the meat-processing sector.

8.2. Materials and methods

8.2.1. Materials

Actual SWW samples, with an average TOC concentration of 862 mg/L, were taken from selected provincially licensed meat processing plants (Ontario, Canada) directly from their source (OMAFRA, 2016). The overall SWW characteristics from the selected meat processing plants are shown in Table 8.1.

Table 8.1. Characteristics of the actual slaughterhouse wastewater from selected provincially licensed meat processing plants with study range values for the combined ABR–AS–UV/H₂O₂ system.

J. Environ. Manage. (2016), *In Press*.

Parameter	Range
BOD (mg/L)	65.15-1,831
COD (mg/L)	76.43-2,166
TN (mg/L)	101.1-366.1
TOC (mg/L)	48.91-1,691
TP (mg/L)	0.1430-31.38
TSS (mg/L)	0.2870-124.3
pH	6.800-7.000

Five sample sites were used in this study due to the wide TOC range of the slaughterhouse effluents obtained from the meat processing plants. Anaerobic and aerobic sludge seeds in

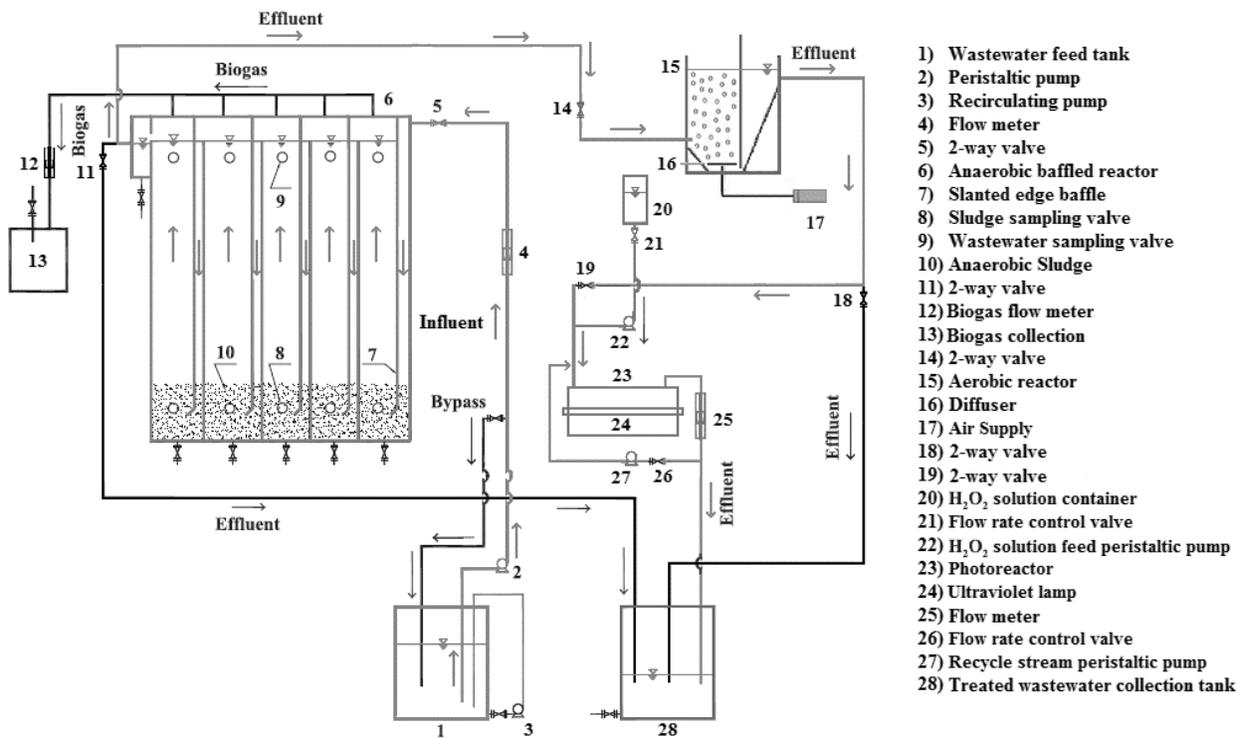
concentrations of 38,000 and 3,000 mg/L, respectively, were obtained from the Ashbridges Bay Wastewater Treatment Plant, a municipal wastewater treatment plant in Toronto, Canada. A hydrogen peroxide solution (30% w/w) was purchased from Sigma-Aldrich (Oakville, ON), whereas NaOH (50% w/w) and H₂SO₄ (98% w/w) were obtained from EMD Millipore (Etobicoke, ON) for pH adjustment. All purchased chemicals were used as received.

8.2.2. Experimental setup

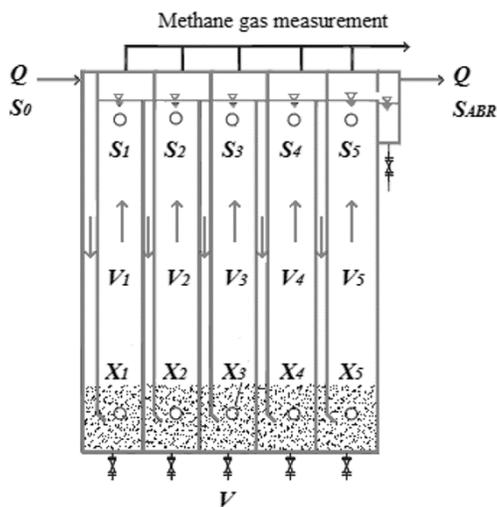
Figure 8.1a illustrates the schematic diagram of the experimental setup for the combined ABR–AS–UV/H₂O₂ processes. The combined system consisted of a 36-L ABR with five equal-volume chambers integrated with individual headspaces and biogas collection piping, a 12.65-L aerobic AS bioreactor with a monitored air flow rate to maintain dissolved oxygen (DO) concentrations over 2.0 mg/L, and a 1.35-L photoreactor with recycle and uniform light distribution. The stainless steel cylindrical photoreactor (Barrier SL-1S – Siemens Inc., Markham, ON) had an external diameter of 8 cm, a length of 34 cm, and a 2.5 cm diameter UV-C lamp inserted into the center of the photoreactor with an output power of 6 W and a 254 nm wavelength. A quartz sleeve covered the lamp to protect it from fouling and maintain a uniform UV-C radiation emission.

8.2.3. Experimental procedure

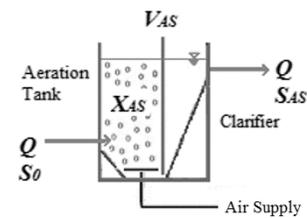
The anaerobic and aerobic sludge seeds were loaded into the anaerobic and aerobic bioreactors, respectively. The inoculum was acclimatized in sixty days by feeding the actual SWW continuously into the bioreactors at a constant flow rate (75 mL/min) while gradually increasing its concentration on biweekly basis from 25, 50, and 75% up to 100% of the actual SWW. Biomass growth within the ABR and AS processes was monitored by collecting samples from each compartment of both ABR and AS bioreactors during the acclimatization period by measuring the concentrations of both total suspended solids (TSS) and volatile suspended solids (VSS). After the acclimatization period, the anaerobic and aerobic biomass concentrations, measured as VSS, were stabilized at 25,000 mg/L and 3,000 mg/L, respectively. The temperature of the processes remained under sub-mesophilic conditions with an average of $24.9 \pm 0.1^\circ\text{C}$ in the combined ABR–AS–UV/H₂O₂ system.



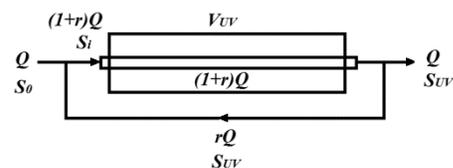
(a) Combined anaerobic-aerobic processes for the treatment of SWW



(b) anaerobic baffled reactor



(c) aerobic activated sludge bioreactor



(d) UV/H₂O₂ photoreactor with recycle

Figure 8.1. Schematic diagram of (a) the combined anaerobic-aerobic processes for the treatment of SWW and the individual processes (b) anaerobic baffled reactor, (c) aerobic activated sludge bioreactor, and (d) UV/H₂O₂ photoreactor with recycle.

J. Environ. Manage. (2016), *In Press*.

After the sixty-day acclimatization period, the following procedure was used during each experiment in the combined ABR–AS–UV/H₂O₂ system for quality control:

- 1) SWW samples were filtered to separate the liquid from the solid portion of the SWW.
- 2) Filtered SWW samples were diluted to reach the desired TOC concentration of the feed in a 120-L solution.
- 3) Sulfuric acid (H₂SO₄) and sodium hydroxide (NaOH) solutions at 98% and 50% w/w, respectively, were used to adjust the pH.
- 4) The SWW solution with the desired TOC concentration and pH was fed to the combined ABR–AS–UV/H₂O₂ system by a variable speed peristaltic pump, which was used to control and adjust the flow rate.
- 5) An adequate H₂O₂ concentration was calculated based on the material balance for each experiment, by which the H₂O₂ solution flow rate to the photoreactor was adjusted and fed by a secondary variable speed peristaltic pump.
- 6) In the photoreactor, there was a recycle stream, for which a third variable speed peristaltic pump was used to adjust the flow rate to the desired recycle ratio.
- 7) Effluent samples were taken at 3-h intervals until the system reached steady state conditions.

8.2.4. Sample analysis

An automated TOC/TN analyzer (Teledyne Tekmar Apollo 9000, Mason, OH) measured both TOC and TN concentrations for each sample. Temperature, pH, and DO were measured daily using a pH meter with a temperature probe (Thermo Scientific Orion 230A+, Ottawa, ON), and a dissolved oxygen meter (YSI 58 Dissolved Oxygen Meter, Yellow Springs, OH), respectively. The concentrations of TSS and VSS were measured according to the standards methods (APHA, 2012). Biogas analysis was performed using a portable gas analyzer (Landtec Biogas 5000, Colton, CA) for CH₄, CO₂, O₂, and N₂-balance in a volume percentage measurement. The H₂O₂ residuals were measured with a UV-visible spectrophotometer (Ultrospec 1100 pro – Amersham Biosciences, Amersham, UK) at 454 nm using the copper (II) ion and 2,9-dimethyl-1,10-phenanthroline (neocuproine) method, also known as the copper-DMP method (Baga et al., 1988; Kosaka et al., 1998; Brandhuber and Korshin, 2009; Hamad et al., 2014, 2016; Bustillo-Lecompte et al., 2016a, 2016b). All experiments were repeated in triplicates, and the average values were reported.

8.2.5. Experimental design

A four-factor with five levels CCD in combination with RSM was used to optimize the overall efficiency of the combined ABR–AS–UV/H₂O₂ system, maximizing the percentual TOC and TN removals and the percentual methane gas yield, as the percent TOC converted to CH₄, while minimizing the percentual H₂O₂ residuals in the effluent of the photoreactor. The influent concentration of TOC (X_1), the flow rate (X_2), the photoreactor inlet concentration of H₂O₂ (X_3), and the pH of the main feed (X_4) were used as independent factors in the DOE. On the other hand, the percentual TOC removal (Y_1), the TN removal (Y_2), the H₂O₂ residuals in the photoreactor effluent (Y_3), and the CH₄ production in the anaerobic bioreactor (Y_4) were considered as process responses. Thus, each factor was coded at five levels, from -2 to +2, as shown in Table 8.2. Experimental data from previous studies were used to determine and select the critical ranges of the factors (Bustillo-Lecompte and Mehrvar, 2015; Bustillo-Lecompte et al., 2013, 2014, 2015, 2016a, 2016b).

Table 8.2. Independent variables with coded levels based on a four-factor, five level CCD for the combined ABR–AS–UV/H₂O₂ system for SWW treatment.

J. Environ. Manage. (2016), *In Press*.

Independent variable	Symbol	Coded levels				
		-2	-1	0	1	2
TOC _{in} (mg/L)	X_1	50	450	850	1,250	1,650
Flow rate (mL/min)	X_2	15	45	75	105	135
H ₂ O ₂ _{in} (mg/L)	X_3	100	300	500	700	900
pH	X_4	3	5	7	9	11

A quadratic model was used to estimate the parametric coefficients by correlating dependent and independent variables using the least-squares regression as shown in Equation (8.1) (Ghafoori et al., 2012, 2014a, 2015; Bustillo-Lecompte et al., 2016a, 2016b):

$$Y_i = \beta_o + \sum_{i=1}^k \beta_i X_i + \sum_{i=1}^k \beta_{ii} X_i^2 + \sum_{i=1}^{k-1} \sum_{j=2}^k \beta_{ij} X_i X_j + c \quad (8.1)$$

where β_o , β_i , β_{ii} , and β_{ij} are the constant, linear, quadratic, and cross-factor interaction coefficients, respectively; X_i and X_j represent the independent variables; Y_i is the predicted response; and k and c are the number of factors and the residual term, respectively.

The statistical software Design-Expert 10.0.0.3 was employed in the DOE to estimate the coefficients of the response functions. The significance of the model equations, individual parameters, and factor interactions were evaluated by analysis of variance (ANOVA) at the confidence intervals (CI) of 95% ($\alpha = 0.05$). Two-dimensional (2D) contour plots and three-dimensional (3D) surface responses were obtained in the quadratic models. Additional experimental runs were carried out to validate the quadratic models for the maximum percentual CH₄ production, the TOC and TN removals, and minimum H₂O₂ residuals in the effluent of the photoreactor at the optimal operating conditions, calculated by the software numerical optimization method.

8.2.6. Optimization of the operating conditions

To obtain a simultaneous objective function that represents the geometric mean of all transformed responses from the DOE, the desirability multiple response method was used to combine the desirable ranges for each response as shown in Equation (8.2) (Myers et al., 2004; Bustillo-Lecompte et al., 2016a, 2016b):

$$D = (d_1 \times d_2 \times d_3 \times d_4 \dots \times d_n)^{1/n} = \left(\prod_{i=1}^n d_i \right)^{1/n} \quad (8.2)$$

where D , d_i , and n are the desirability objective function, each response range, and the number of responses, respectively. For a simultaneous optimization, each response requires low and high values for the optimization. Otherwise, if any response is found outside its desirability range, the overall desirability becomes equal to zero. In this case, the percentual TOC removal (d_1), TN removal (d_2), H₂O₂ residual (d_3), and CH₄ production (d_4) are optimized.

8.2.7. Slaughterhouse wastewater degradation models

In this study, the combined anaerobic-aerobic bioreactors and UV/H₂O₂ with recycle were used in sequence to degrade an actual SWW in continuous mode at the laboratory scale. A simple model represents the biological treatment as a continuous anaerobic plug flow reactor (PFR) followed by a

continuous aerated stirred tank reactor (CSTR), using first order kinetics and a biomass term to account for the rate of the limiting substrate consumption in the system. In the photochemical reactor, depending on the order of the reactions, the compound could be mineralized after treatment in the bioreactors.

8.2.7.1. Slaughterhouse wastewater degradation in a continuous anaerobic baffled reactor

The ABR can be considered as a continuous PFR, as illustrated in Figure 8.1b. The first order kinetic model shown below is used to describe the limiting substrate consumption:

$$\frac{1}{X} \frac{dS}{dt} = -kS \quad (8.3)$$

where S is the limiting substrate concentration (mg/L), X is the concentration of the active reactor biomass (mg/L), and k is the first order rate constant (L/mg.h), which could be calculated from the SWW treatment data knowing the substrate concentration and biomass in each of the ABR compartments. The substrate in an actual slaughterhouse wastewater is a multicomponent mixture; therefore, the TOC concentration was considered as a surrogate parameter for all organic substrates. This model assumes soluble components in the ABR and the system to be representative of an n -CSTR-in-series, where n represents the number of compartments of the ABR.

The model uses the material balance shown in Equation (8.4) for the first compartment, and assumes that CH_4 production is the rate-limiting step since the total biomass concentration is used without recycle (Kennedy and Barriault, 2007).

$$\frac{dS}{dt} V_1 = QS_{in} - QS_1 - k_1 S_1 X_1 V_1 \quad (8.4)$$

where S_{in} is the influent limiting substrate concentration (mg/L), k_1 is the first order rate coefficient in the first compartment (L/mg.h), V_1 is the volume of the first compartment, X_1 is the concentration of biomass in the first compartment (mg/L), and Q is the influent substrate flow rate (L/h). Thus, solving by integration, the effluent concentration for the first compartment at steady state without recycle is shown in Equation (8.5):

$$S_1 = \frac{S_{in}}{(1 + k_1 X_1 V_1 / Q)} \quad (8.5)$$

Consequently, the overall equation for the final effluent of an ABR with five compartments at steady state without recycle (S_{ABR}) is as follows:

$$S_{ABR} = \frac{S_{in}}{(1 + k_1 X_1 V_1 / Q)(1 + k_2 X_2 V_2 / Q)(1 + k_3 X_3 V_3 / Q)(1 + k_4 X_4 V_4 / Q)(1 + k_5 X_5 V_5 / Q)} \quad (8.6)$$

8.2.7.2. Slaughterhouse wastewater degradation in a continuous completely-mixed activated sludge bioreactor

The completely mixed AS bioreactor (Figure 8.1c) is a CSTR. The effluent concentration found by material balance and growth relationships between the limiting substrate and biological cell mass is as follows (Reynolds and Yang, 1966):

$$S_{AS} = \frac{S_{in}}{(1 + k_{AS} X_{AS} V_{AS} / Q)} \quad (8.7)$$

where k_{AS} is the first order reaction rate constant in the AS bioreactor (L/mg.h), S_{in} is the concentration of substrate (TOC) in the influent of the AS bioreactor (mg/L), S_{AS} is the final effluent substrate (TOC) concentration in the AS bioreactor (mg/L), X_{AS} is the biomass concentration in the AS bioreactor (mg/L), V_{AS} is the volume of the AS bioreactor (L), and Q is the influent substrate flow rate (L/h).

8.2.7.3. Slaughterhouse wastewater degradation in a continuous UV/H₂O₂ photoreactor with recycle

In the UV/H₂O₂ photoreactor with recycle (Figure 1d), the recycled stream is drawn off from a point near the effluent and merged with the feed into the photoreactor. Then, the recycle ratio parameter, r , can be defined as the ratio of recycle flow rate to the main feed flow rate to the photoreactor. The only new step in calculating the conversion for a recycle reactor is a material balance at the stream intersections to properly express the species concentrations as a function of conversion. Thus, from the material balance at the photoreactor inlet, the following equation is written:

$$QS_{in} + rQS_{UV} = (1+r)QS_r \quad (8.8)$$

where S_{UV} is the concentration of the substrate (TOC) in the effluent of the UV/H₂O₂ photoreactor (mg/L), S_{in} is the influent substrate (TOC) concentration (mg/L), S_r is the concentration of the substrate (TOC) in the stream fed to the photoreactor, r is the recycle ratio, and Q is the influent substrate flow rate (L/h). By solving for S_r :

$$S_r = \frac{S_{in} + rS_{UV}}{1+r} \quad (8.9)$$

Simultaneously, from the material balance in the photoreactor using time-based pseudo first-order reaction, as demonstrated in previous studies (Edalatmanesh et al., 2008; Shu et al., 2013; Bustillo-Lecompte et al., 2014, 2016a), the following equations are obtained:

$$\frac{dS}{dt}V_{UV} = (1+r)QS_r - (1+r)Q(S_r - dS_r) + k'S_r dV \quad (8.10)$$

$$\frac{dS}{dt}V_{UV} = QdS_r(1+r) + k'S_r dV \quad (8.11)$$

where V_{UV} is the volume of the photoreactor and k' is the sum of the direct photolysis rate (k_{UV}) and the hydroxyl radical (\cdot OH) oxidation rate or indirect photolysis rate ($k_{\cdot OH}$). Equation (11) at steady state is written as follows:

$$S_{UV} = S_r \times \exp\left(\frac{-k'V_{UV}}{(1+r)Q}\right) \quad (8.12)$$

The direct photolysis rate (k_{UV}) is described as follows:

$$k_{UV} = K_s \times \phi_{SWW} \quad (8.13)$$

where ϕ_{SWW} is the quantum yield for the SWW calculated by Equation (8.14) and K_s is the specific rate of light absorption of the target compound calculated by Equation (8.15).

$$\phi_{SWW} = \frac{k_{UV} \times U}{\ln(10) \times \varepsilon_s} \quad (8.14)$$

$$K_s = \frac{E^0 \times \varepsilon_s \times (1 - 10^{-\alpha \ell})}{\alpha \ell} \quad (8.15)$$

where U is the molar photon energy (4.72×10^5 J/E at 254 nm), ε_s is the molar attenuation coefficient for the targeted substrate (1/M.cm), E^0 is the incident photon irradiance (W/cm^2), ℓ is the solution depth or path length (cm), and α is the absorbance (1/cm) of the solution calculated by Equation (8.16). Considering the water background, H_2O_2 as the oxidant, and the SWW targeted substrate (Shu et al., 2013):

$$\alpha = \alpha_0 + \varepsilon_{\text{H}_2\text{O}_2} \times [\text{H}_2\text{O}_2] + \varepsilon_s \times [S_r] \quad (8.16)$$

On the other hand, the oxidation rate ($k_{\cdot\text{OH}}$) is described as follows:

$$k_{\cdot\text{OH}} = K_{\cdot\text{OH}/\text{SWW}} \times [\cdot\text{OH}]_{\text{SS}} \quad (8.17)$$

where $k_{\cdot\text{OH}/\text{SWW}}$ is the second-order rate constant describing the reaction between the $\cdot\text{OH}$ and a targeted substrate in SWW and $[\cdot\text{OH}]_{\text{SS}}$ is the steady state concentration of $\cdot\text{OH}$ formed via H_2O_2 photolysis calculated by Equation (8.18), considering the scavenging effect ($\sum K_{\cdot\text{OH}/\text{sv}} \times [\text{sv}]$) as follows (Baeza and Knappe, 2011):

$$[\cdot\text{OH}]_{\text{SS}} = \frac{K_{\text{H}_2\text{O}_2} \times \phi_{\text{H}_2\text{O}_2} \times [\text{H}_2\text{O}_2]}{\sum K_{\cdot\text{OH}/\text{sv}} \times [\text{sv}]} \quad (8.18)$$

8.2.8. Economics study

In order to gain the maximum benefit from the combined system, the residence time of the wastewater in each reactor should be optimized and the constraints should be considered in the model along with its limitations. Therefore, three objective functions were defined including the retention time

minimization, the total power consumption minimization, and the overall treatment cost minimization using a cost-effectiveness analysis (CEA).

8.3. Results and discussion

8.3.1. *Experimental design and statistical analysis*

The influent TOC concentration was selected as the targeted substrate and one of the factors to be evaluated by DOE since TOC analysis provides a more efficient and accurate appraisal of the total organic compounds present in a wastewater sample in comparison to biological oxygen demand (BOD) or chemical oxygen demand (COD), due to the rapid sampling methodology using an automatized TOC analyzer without producing any toxic analytical waste (Dubber and Gray, 2010; Bustillo-Lecompte et al., 2014; Bustillo-Lecompte and Mehrvar, 2015). The flow rate and the pH were also selected due to their direct relationship to microorganism activity and growth (Chan et al., 2009; Cao and Mehrvar, 2011; Mees et al., 2014; Bustillo-Lecompte et al., 2013; Bustillo-Lecompte and Mehrvar, 2015). Whereas, the inlet concentration of H_2O_2 was selected since it is the oxidant used in the AOP for the post-treatment of the slaughterhouse wastewater (Bustillo-Lecompte and Mehrvar, 2015; Bustillo-Lecompte et al., 2013, 2014, 2015, 2016a, 2016b).

Table 8.3 portrays the four-factor, five-level CCD with observed and predicted values for the percentual TOC removal (Y_1), TN removal (Y_2), H_2O_2 residual (Y_3), and CH_4 production (Y_4) by the developed quadratic models related to the combined ABR–AS–UV/ H_2O_2 system for SWW treatment. The response surface methodology (RSM) was used for parameter estimation, specifying the correlation between the input factors and the output responses, as previously shown in Equation (1). Consequently, in order to estimate the response functions for Y_1 , Y_2 , Y_3 , and Y_4 , second-order polynomial Equations were developed in terms of the coded factors, including the influent concentration of the TOC (X_1), the flow rate (X_2), the inlet concentration of H_2O_2 (X_3), and the pH (X_4). The coefficients for each model parameter are presented in Table 8.4.

Negative coefficients for the model components X_1 , X_2 , X_3 , X_4 , X_1X_2 , X_1X_3 , X_1X_4 , X_3X_4 , X_2^2 , X_3^2 , and X_4^2 in Y_1 ; X_1 , X_2 , X_3 , X_1X_4 , X_3^2 , and X_4^2 in Y_2 ; X_1 , X_1X_2 , X_1X_3 , X_2X_3 , and X_2^2 in Y_3 ; and X_2 , X_4 , X_1X_2 , X_1^2 , X_2^2 , X_3^2 , and X_4^2 in Y_4 indicate unfavorable effects on the percentual TOC removal, the TN removal, the H_2O_2 residuals in the effluent, and the CH_4 production, respectively.

Table 8.3. Four-factor, five-level CCD with observed and predicted percentual TOC removal, TN removal, H₂O₂ residual, and CH₄ production values.

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Run	Independent coded variables				TOC removal (%)		TN removal (%)		H ₂ O ₂ residual (%)		CH ₄ production (%)	
	X ₁	X ₂	X ₃	X ₄	Observed	Predicted	Observed	Predicted	Observed	Predicted	Observed	Predicted
1	-1	-1	-1	-1	88.74	88.85	84.89	85.64	1.51	1.53	55.99	54.89
2	1	-1	-1	-1	83.11	83.01	77.77	77.87	1.78	1.78	62.58	62.69
3	-1	1	-1	-1	86.64	86.33	67.09	66.84	1.74	1.77	54.88	55.37
4	1	1	-1	-1	78.42	78.60	61.62	61.42	1.92	1.94	49.08	49.64
5	-1	-1	1	-1	94.16	94.26	77.27	77.33	1.72	1.74	53.10	52.52
6	1	-1	1	-1	83.29	83.37	79.27	79.99	1.84	1.87	62.72	63.83
7	-1	1	1	-1	95.51	95.01	59.76	60.01	1.91	1.91	54.64	54.16
8	1	1	1	-1	82.58	82.24	65.04	65.03	1.93	1.95	52.35	51.95
9	-1	-1	-1	1	91.32	91.53	85.03	84.21	1.56	1.55	50.28	50.42
10	1	-1	-1	1	84.25	84.46	69.60	70.29	1.42	1.46	59.13	59.59
11	-1	1	-1	1	90.68	90.31	75.58	75.81	2.14	2.15	54.88	53.75
12	1	1	-1	1	81.58	81.35	65.15	64.25	1.98	1.97	49.08	49.40
13	-1	-1	1	1	84.72	84.25	79.34	80.49	1.90	1.92	50.34	49.76
14	1	-1	1	1	71.97	72.14	77.60	77.01	1.71	1.69	63.21	62.45
15	-1	1	1	1	86.34	86.30	74.51	73.58	2.42	2.44	54.64	54.26
16	1	1	1	1	72.71	72.31	72.26	72.45	2.11	2.13	52.35	53.43
17	-2	0	0	0	99.89	100.0	81.82	81.66	2.01	1.98	52.56	54.22
18	2	0	0	0	80.48	80.48	72.70	72.76	1.95	1.93	62.56	61.18
19	0	-2	0	0	88.15	87.78	90.38	89.41	1.39	1.37	58.28	58.73
20	0	2	0	0	84.63	85.42	65.18	66.05	2.08	2.05	50.35	50.18
21	0	0	-2	0	84.31	84.24	69.12	69.37	1.71	1.69	57.75	57.69
22	0	0	2	0	80.11	80.60	69.62	69.26	2.09	2.06	58.99	59.34
23	0	0	0	-2	82.62	82.79	66.47	65.82	1.84	1.80	50.35	50.35
24	0	0	0	2	75.28	75.53	71.26	71.81	2.01	2.00	47.07	47.35
25	0	0	0	0	86.85	86.67	76.25	76.30	1.73	1.75	62.51	60.30
26	0	0	0	0	85.95	86.67	75.75	76.30	1.73	1.75	59.89	60.30
27	0	0	0	0	86.81	86.67	75.16	76.30	1.75	1.75	58.89	60.30
28	0	0	0	0	86.30	86.67	76.86	76.30	1.76	1.75	59.37	60.30
29	0	0	0	0	87.53	86.67	77.35	76.30	1.78	1.75	60.72	60.30
30	0	0	0	0	86.60	86.67	76.40	76.30	1.75	1.75	60.44	60.30

Table 8.4. Coefficients table for the percentual TOC removal, TN removal, H₂O₂ residual, and CH₄ production quadratic models.

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Response	Intercept	X_1	X_2	X_3	X_4	X_1X_2	X_1X_3	X_1X_4	X_2X_3	X_2X_4	X_3X_4	X_1^2	X_2^2	X_3^2	X_4^2
$Y_1 = \text{TOC}_{\text{removal}}$	86.71	-4.96	-0.59	-0.91	-1.82	-0.47	-1.26	-0.31	0.82	0.33	-3.17	0.93	-0.02	-1.06	-1.88
$Y_2 = \text{TN}_{\text{removal}}$	76.30	-2.23	-5.84	-0.03	1.50	0.59	2.61	-1.53	0.37	2.60	1.15	0.23	0.36	-1.75	-1.87
$Y_3 = \text{H}_2\text{O}_2_{\text{residual}}$	1.73	-0.01	0.17	0.09	0.05	-0.02	-0.03	-0.09	-0.02	0.09	0.04	0.05	-0.01	0.03	0.04
$Y_4 = \text{CH}_4_{\text{production}}$	60.30	1.74	-2.14	0.41	-0.75	-3.38	0.88	0.34	0.29	0.71	0.43	-0.65	-1.46	-0.45	-2.86

On the other hand, positive coefficients for X_2X_3 , X_2X_4 , and X_1^2 in Y_1 ; X_4 , X_1X_2 , X_1X_3 , X_2X_3 , X_2X_4 , X_3X_4 , X_1^2 , and X_2^2 in Y_2 ; X_2 , X_3 , X_4 , X_2X_4 , X_3X_4 , X_1^2 , X_3^2 , and X_4^2 in Y_3 ; and X_1 , X_3 , X_1X_3 , X_1X_4 , X_2X_3 , X_2X_4 , and X_3X_4 in Y_4 indicate favorable effects on the percentual TOC removal, the TN removal, the H_2O_2 residuals, and the CH_4 production, respectively. Coefficients with values close to zero represent lower relative intensity; thus, X_2^2 do not intensely affect the percentual TOC removal, X_3 do not intensely affect the percentual TN removal, and X_1 , X_1X_2 , X_1X_3 , X_2X_3 , X_2^2 , and X_3^2 do not intensely affect the percentual H_2O_2 residuals. However, the significance of the quadratic model must be evaluated to establish the actual effect of each model parameter as well as their interaction using statistical analysis. Consequently, ANOVA was employed with a 95% CI to estimate the statistical significance of the four quadratic models for the percentual TOC removal (Y_1), the TN removal (Y_2), the H_2O_2 residual (Y_3), and the CH_4 production (Y_4) as shown in Table 8.5.

Table 8.5. ANOVA of the prediction results for the percentual TOC removal, TN removal, H_2O_2 residual, and CH_4 production by quadratic modeling.

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Source	Sum of squares	df ^a	Mean square	F value ^b	p-value ^c	Remark
TOC _{removal} model	1065.3	14	76.094	288.16	<0.0001	Significant
$X_1 = TOC_{in}$	590.44	1	590.44	2235.9	<0.0001	Significant
$X_2 = \text{Flow rate}$	8.3308	1	8.3308	31.548	<0.0001	Significant
$X_3 = H_2O_2_{in}$	19.947	1	19.947	75.538	<0.0001	Significant
$X_4 = \text{pH}$	79.134	1	79.134	299.67	<0.0001	Significant
X_1X_2	3.5721	1	3.5721	13.527	0.0022	Significant
X_1X_3	25.452	1	25.452	96.384	<0.0001	Significant
X_1X_4	1.5129	1	1.5129	5.7292	0.0302	Significant
X_2X_3	10.726	1	10.726	40.617	<0.0001	Significant
X_2X_4	1.6900	1	1.6900	6.3999	0.0231	Significant
X_3X_4	160.91	1	160.91	609.35	<0.0001	Significant
X_1^2	23.755	1	23.755	89.957	<0.0001	Significant
X_2^2	0.0090	1	0.0090	0.0341	0.8559	Not significant
X_3^2	31.001	1	31.001	117.40	<0.0001	Significant
X_4^2	96.750	1	96.750	366.38	<0.0001	Significant
Residual	3.9610	15	0.2641			
Lack of Fit	2.5093	10	0.2509	0.8642	0.6067	Not significant
Pure error	1.4517	5	0.2903			
Corrected total SS ^d	1069.3	29				
R^2	0.9963					
Adjusted R^2	0.9928					
Adequate Precision	77.555					

Source	Sum of squares	df ^a	Mean square	F value ^b	p-value ^c	Remark
TN _{removal} model	1460.7	14	104.33	135.64	<0.0001	Significant
X ₁ = TOC _{in}	118.82	1	118.82	154.46	<0.0001	Significant
X ₂ = Flow rate	818.53	1	818.53	1064.1	<0.0001	Significant
X ₃ = H ₂ O ₂ in	0.0193	1	0.0193	0.0250	0.8764	Not significant
X ₄ = pH	53.820	1	53.820	69.968	<0.0001	Significant
X ₁ X ₂	5.5460	1	5.5460	7.2101	0.0170	Significant
X ₁ X ₃	108.89	1	108.89	141.56	<0.0001	Significant
X ₁ X ₄	37.638	1	37.638	48.931	<0.0001	Significant
X ₂ X ₃	2.2052	1	2.2052	2.8669	0.1111	Not significant
X ₂ X ₄	108.26	1	108.26	140.75	<0.0001	Significant
X ₃ X ₄	21.114	1	21.114	27.449	0.0001	Significant
X ₁ ²	1.4196	1	1.4196	1.8455	0.1944	Not significant
X ₂ ²	3.5055	1	3.5055	4.5573	0.0497	Significant
X ₃ ²	83.521	1	83.521	108.58	<0.0001	Significant
X ₄ ²	96.043	1	96.043	124.86	<0.0001	Significant
Residual	11.538	15	0.7692			
Lack of Fit	8.5076	10	0.8508	1.4036	0.3719	Not significant
Pure error	3.0306	5	0.6061			
Corrected total SS ^d	1472.2	29				
R ²	0.9922					
Adjusted R ²	0.9848					
Adequate Precision	47.394					
H ₂ O ₂ residual model	1.3651	14	0.0975	115.39	<0.0001	Significant
X ₁ = TOC _{in}	0.0043	1	0.0043	5.0493	0.0401	Significant
X ₂ = Flow rate	0.6801	1	0.6801	804.81	<0.0001	Significant
X ₃ = H ₂ O ₂ in	0.2054	1	0.2054	243.02	<0.0001	Significant
X ₄ = pH	0.0600	1	0.0600	71.006	<0.0001	Significant
X ₁ X ₂	0.0064	1	0.0064	7.5740	0.0148	Significant
X ₁ X ₃	0.0169	1	0.0169	20.000	0.0004	Significant
X ₁ X ₄	0.1190	1	0.1190	140.86	<0.0001	Significant
X ₂ X ₃	0.0064	1	0.0064	7.5740	0.0148	Significant
X ₂ X ₄	0.1190	1	0.1190	140.86	<0.0001	Significant
X ₃ X ₄	0.0210	1	0.0210	24.882	0.0002	Significant
X ₁ ²	0.0732	1	0.0732	86.650	<0.0001	Significant
X ₂ ²	0.0032	1	0.0032	3.8095	0.0699	
X ₃ ²	0.0254	1	0.0254	30.031	0.0001	Significant
X ₄ ²	0.0394	1	0.0394	46.667	<0.0001	Significant
Residual	0.0127	15	0.0008			
Lack of Fit	0.0109	10	0.0011	3.0208	0.1170	Not significant
Pure error	0.0018	5	0.0004			
Corrected total SS ^d	1.3778	29				
R ²	0.9908					
Adjusted R ²	0.9822					
Adequate Precision	51.306					

Source	Sum of squares	df ^a	Mean square	F value ^b	p-value ^c	Remark
CH ₄ production model	666.11	14	47.579	34.394	<0.0001	Significant
X ₁ = TOC _{in}	72.628	1	72.628	52.500	<0.0001	Significant
X ₂ = Flow rate	109.70	1	109.70	79.296	<0.0001	Significant
X ₃ = H ₂ O ₂ in	4.1085	1	4.1085	2.9699	0.1054	Not significant
X ₄ = pH	13.485	1	13.485	9.7479	0.0070	Significant
X ₁ X ₂	182.99	1	182.99	132.28	<0.0001	Significant
X ₁ X ₃	1.8980	1	1.8980	1.3716	0.2598	Not significant
X ₁ X ₄	12.373	1	12.3728	8.9439	0.0091	Significant
X ₂ X ₃	1.3631	1	1.3631	0.9853	0.3366	Not significant
X ₂ X ₄	8.1653	1	8.1653	5.9024	0.0282	Significant
X ₃ X ₄	2.9670	1	2.9670	2.1448	0.1637	Not significant
X ₁ ²	11.592	1	11.592	8.3797	0.0111	Significant
X ₂ ²	58.575	1	58.575	42.342	<0.0001	Significant
X ₃ ²	5.4953	1	5.4953	3.9724	0.0648	
X ₄ ²	224.76	1	224.76	162.47	<0.0001	Significant
Residual	20.751	15	1.3834			
Lack of Fit	12.650	10	1.2650	0.7807	0.6554	Not significant
Pure error	8.1011	5	1.6202			
Corrected total SS ^d	686.86	29				
R ²	0.9698					
Adjusted R ²	0.9416					
Adequate Precision	19.812					

a. Degrees of freedom (*df*)

b. Fisher's (*F*) exact test value.

c. A probability value (*p*) < 0.05 is considered significant, a *p*-value > 0.10 is considered not significant.

d. Total sum of squares corrected for the mean.

Consequently, each factor coefficient was evaluated in terms of statistical significance using the Fisher's (*F*) exact test by comparing probability (*p*) values greater than *F*. Thus, small probability values (*p* < 0.05) indicate the significance of the model parameters, whereas *p*-values > 0.10 indicate the non-significance of the model factors, as indicated in the sixth column of Table 8.5. Probability values between 0.05 and 0.10 provide weak evidence against the null hypothesis and, by convention, are not considered low enough to justify rejecting it and requires further analysis. For instance, X₂² and X₃² had *p*-values between 0.05 and 0.10 for the H₂O₂ and the CH₄ models, respectively. Thus, the non-significance of the quadratic effect is an appropriate designation since it indicates the optimal levels are located at the limits of the experimental region (Bustillo-Lecompte et al., 2016a).

As shown in Table 8.5, the developed quadratic models for each response were found to be significant. F -values of 288.16, 135.64, 115.39, and 34.39 were obtained for the percentual TOC removal (Y_1), the TN removal (Y_2), the H_2O_2 residuals (Y_3), and the CH_4 production (Y_4), respectively. Furthermore, the accuracy of the developed models to predict the response functions was confirmed by small probability values ($p < 0.05$). However, some model terms were found to be not significant ($p > 0.10$), including X_2^2 for the percentual TOC removal, X_3 , X_2X_3 , and X_1^2 for the percentual TN removal, and X_3 , X_1X_3 , X_2X_3 , and X_3X_4 , for the percentual methane production. These non-significant model terms could be expected to have this outcome due to their participation in each stage of the combined system. For instance, it is expected that the inlet H_2O_2 concentration and its combination with other model parameters do not have any significant effect on the percentual TN removal and methane production, since these two responses are more related to the biological treatment, not the AOP.

Besides, the adequate precision of the percentual TOC removal (Y_1), the TN removal (Y_2), the H_2O_2 residual (Y_3), and the CH_4 production (Y_4) were 77.55, 47.39, 51.31, and 19.81, respectively. Because all adequate precision values were greater than 4.00, the developed models can be used to navigate the CCD space (Bustillo-Lecompte, et al., 2016a). Moreover, the p -values for the lack of fit in the models were calculated to be 0.6067, 0.3719, 0.1170, and 0.6554 for the percentual TOC removal (Y_1), the TN removal (Y_2), the H_2O_2 residuals (Y_3), and the CH_4 production (Y_4), respectively. Consequently, a non-significant lack of fit ($p > 0.10$) is desirable, indicating the model fits the data well. Additionally, the model goodness of fit was validated by the determination coefficient (R^2) and the adjusted R^2 , which ensures the adequate variation of the quadratic model in terms of the experimental values. R^2 and adjusted R^2 values for the percentual TOC removal (Y_1), the TN removal (Y_2), the H_2O_2 residuals (Y_3), and the CH_4 production (Y_4) were 0.9963 and 0.9928, 0.9922 and 0.9848, 0.9908 and 0.9822, and 0.9698 and 0.9416, respectively. Thus, the obtained R^2 and adjusted R^2 values for each model represent a high model significance.

On the other hand, the assumption of the constant variance was verified by plotting the internally studentized residual versus predicted values shown in the supplementary materials (Figure S.1). The studentized residuals were found by the ratio of the residuals to an estimate of their standard deviations showing a randomly scattered pattern within the outlier detection limits -3 and $+3$. Moreover, the correlation between the observed and predicted values showed minor discrepancies represented by a straight-line trend, which indicates a good agreement between observed and predicted values.

Therefore, model predictions for the percentual TOC removal, the TN removal, the H₂O₂ residuals, and the CH₄ production, respectively, are satisfactory.

8.3.2. Individual effect of model parameters

The significance of each model parameter was also evaluated using the *F* exact test and *p*-values for each factor including linear, quadratic, and cross-factor interaction. As shown in Table 8.5, *p*-values lower than 0.05 identify model coefficients as significant. Therefore, the influent TOC concentration (X_1), the flow rate (X_2), and the pH (X_4) showed significant effect on all responses while the inlet concentration of H₂O₂ (X_3) was found to be significant only on the percentual TOC removal (Y_1) and the H₂O₂ residual (Y_3) based on the *p*-value. As mentioned in the previous section, it is expected that the inlet concentration of H₂O₂ does not have a significant effect on the percentual TN removal and methane production, since these two responses are more related to the biological treatment stages of the combined system.

Figure 8.2 illustrates the effect of the influent TOC concentration, the flow rate, the inlet concentration of H₂O₂, and the pH on the TOC removal, TN removal, H₂O₂ residual, and CH₄ yield, in the combined ABR–AS–UV/H₂O₂ processes. All responses are shown in the y-axis in percentage (%) units, excepting H₂O₂ residual, which is presented in per mil (‰) for scaling purposes. The model predicted values along with the CI bands for the individual effect of model parameters on the TOC removal, TN removal, H₂O₂ residual, and CH₄ yield are shown in the supplementary materials Figures S.2 to S.5, respectively.

It can be observed that the influent TOC concentration and the flow rate are inversely proportional to both the percentual TOC and TN removals, being slightly affected in the case of the flow rate influence on the TOC removal. This slight effect refers to the mass transfer as a non-limiting factor on the TOC degradation; thus, the TOC removal is due to reactions only. Moreover, there is an optimum inlet concentration of H₂O₂ required for maximum percentual TOC in the UV/H₂O₂ process as well as no requirements to adjust pH for both maximum TOC and TN removal. On the other hand, results indicate that an optimum value for influent TOC concentration and no pH adjustment are required to achieve a minimum H₂O₂ residual in the effluent; whereas, both flow rate and the inlet H₂O₂ concentration are proportional to the H₂O₂ residual, the minimum residual is obtained at the low flow rate and low inlet concentration of H₂O₂.

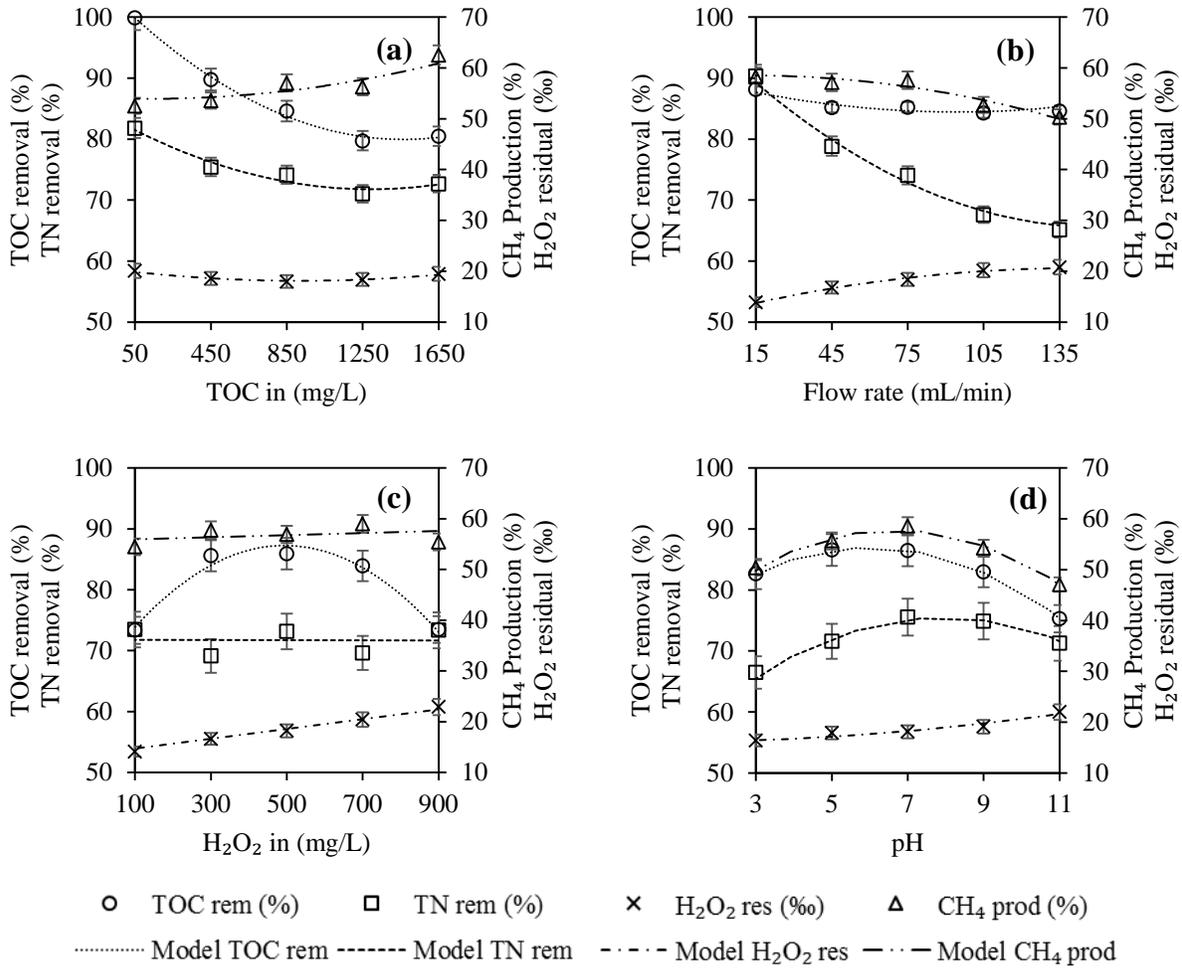


Figure 8.2. Individual effect of the (a) influent concentration of TOC; (b) flow rate; (c) inlet H₂O₂ concentration; and (d) pH on the percentual TOC removal, TN removal, H₂O₂ residual, and CH₄ yield. The dashed lines represent model predicted values, whereas the marker points represent the experimental values. Error bars represent the standard deviation of the experimental data.
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Finally, the inlet concentration of H_2O_2 was not significant on both the CH_4 production and TN removal since those responses are directly representative of the ABR stage of the combined process only. The predicted values demonstrate that to achieve a maximum methane yield, a high influent TOC concentration is needed while optimum flow rate and no pH adjustments are required.

8.3.3. Interaction of model parameters, 2D contour plots, and 3D response surface

The cross-factor interactions between independent variables were plotted into the 2D contour plots and 3D surfaces shown in Figure 8.3. The cross-factor interaction effect between the influent TOC concentration and the inlet concentration of H_2O_2 (X_1X_3) and between the inlet concentration of H_2O_2 and the pH on the percentual TOC removal, in the combined ABR–AS–UV/ H_2O_2 processes, are shown in Figures 8.3a and 8.3b, respectively. Thus, an optimum TOC removal was achieved when there was an optimum inlet concentration of H_2O_2 , while the influent TOC concentration was minimum (Figure 8.3a). Similarly, the inlet concentration of H_2O_2 in the photoreactor of the combined ABR–AS–UV/ H_2O_2 processes should be also optimum at low pH to achieve a maximum removal as shown in Figure 8.3b.

Figures 8.3c and 8.3d depict the effect on the percentual TN removal by the interaction of the influent TOC concentration with the pH (X_1X_4) and the interaction of the flow rate with the pH (X_2X_4), respectively, in the anaerobic-aerobic stage of the combined ABR–AS–UV/ H_2O_2 processes. It can be inferred that at the low influent TOC concentrations with an optimum pH, it is possible to achieve a maximum TN removal (Figure 8.3c). In contrast, the maximum TN removal was achieved with an optimum pH when the flow rate was minimum (i.e. at high residence time in the biological stages of the combined ABR–AS–UV/ H_2O_2 processes), as presented in Figure 8.3d.

Moreover, Figures 8.3e and 8.3f portray the effect of the influent TOC concentration with the inlet concentration of H_2O_2 in the photoreactor (X_1X_3) and the effect of the flow rate with the pH (X_2X_4) on the percentual H_2O_2 residual, respectively, in the effluent of the combined ABR–AS–UV/ H_2O_2 processes. A minimum H_2O_2 concentration in the effluent was achieved at low inlet concentration of H_2O_2 with an optimum influent TOC concentration in the influent (Figure 8.3e) as well as the minimum flow rate with an optimum pH in the combined ABR–AS–UV/ H_2O_2 processes (Figure 8.3f).

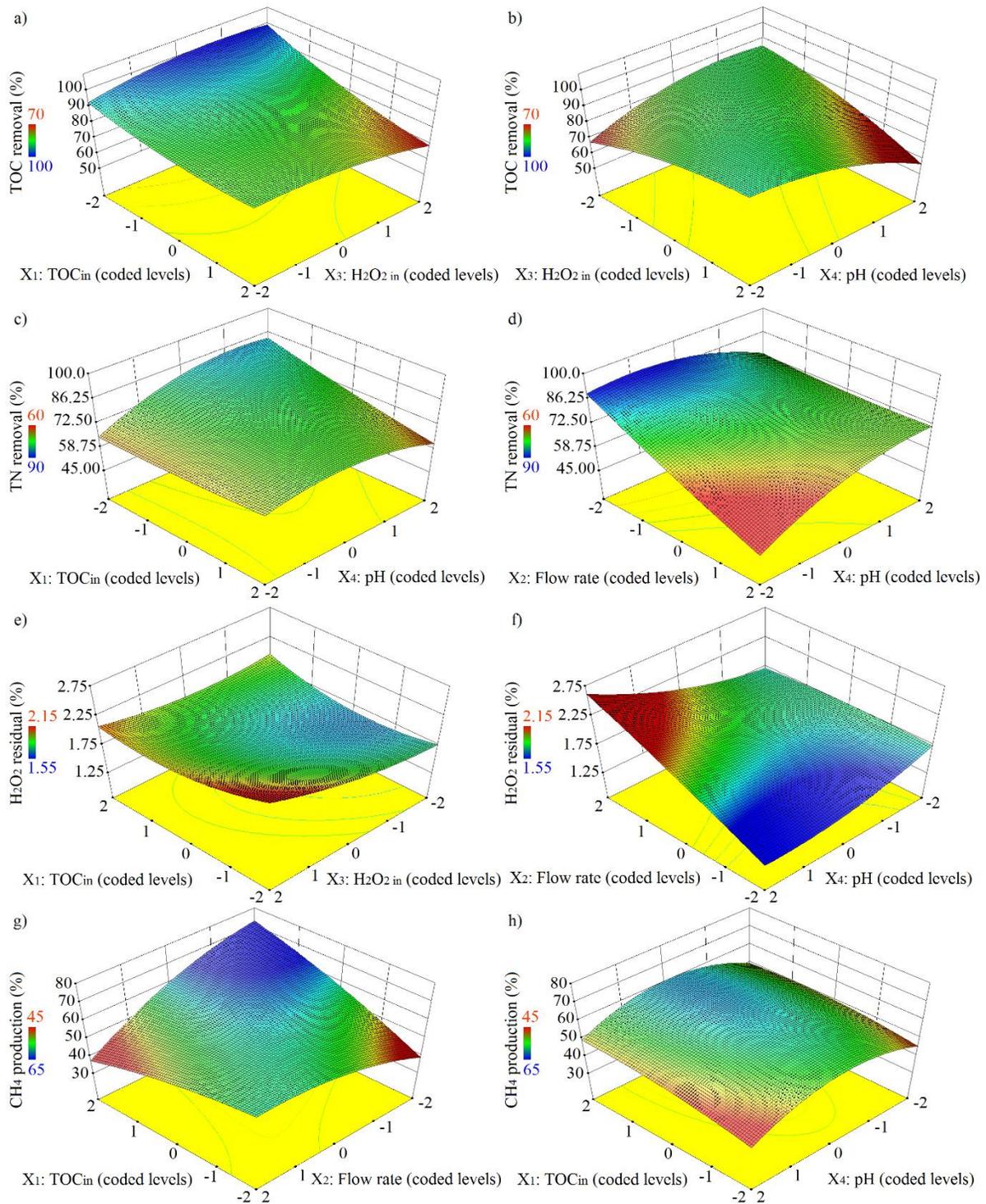


Figure 8.3. 3D surfaces and 2D plots of the interaction effects of (a) the influent TOC concentration with inlet H₂O₂ concentration (X_1X_3) and (b) the inlet H₂O₂ concentration with pH (X_3X_4) on the percentual TOC removal; (c) the influent TOC concentration with pH (X_1X_4) and (d) the flow rate with pH (X_2X_4) on the percentual TN removal; (e) the influent TOC concentration with inlet H₂O₂ concentration (X_1X_3) and (f) the flow rate with pH (X_2X_4) on the percentual H₂O₂ residual; and (g) the influent TOC concentration with flow rate (X_1X_2) and (h) the influent TOC concentration with pH (X_1X_4) on the CH₄ production in the combined ABR–AS–UV/H₂O₂ processes.

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Finally, Figures 8.3g and 8.3h represent the cross-factor interaction effect of the influent TOC concentration with the flow rate (X_1X_2) and the effect of the influent TOC concentration with pH (X_1X_4) on the CH₄ production, respectively, in the anaerobic stage of the combined ABR–AS–UV/H₂O₂ processes. To achieve a maximum CH₄ yield, it is necessary to have a high influent TOC concentration at a low flow rate (Figure 8.3g) and optimum pH (Figure 8.3h).

8.3.4. Optimization of operating conditions and process parameters

The RSM was used to determine the optimum experimental conditions of the four independent variables, including the influent concentration of TOC (X_1), flow rate (X_2), the inlet concentration of H₂O₂ (X_3), and the pH (X_4) to obtain maximum percentual TOC removal, the TN removal, and the CH₄ production with minimum H₂O₂ residual. The optimization was accomplished at defined optimization conditions using the built-in numerical optimization method of the statistical software Design-Expert 10.0.0.3. The response equations shown in Table 8.4 were defined as objective functions and the independent factors in their critical range were used as constraints. The numerical optimization method explores the design space using the developed models to find the optimum factor conditions that meet the previously set goals of maximum percentual TOC removal, the TN removal, and the CH₄ production with minimum H₂O₂ residual, simultaneously.

The multiple response approach shown in Equation (8.2) was used to obtain the desirability parameter interaction plots (Figure 8.4) at optimum factor settings by maximizing the percentual TOC removal (d_1), the TN removal (d_2), and the CH₄ production (d_3) while minimizing the H₂O₂ residual in the effluent (d_4) by numerical optimization in the combined ABR–AS–UV/H₂O₂ processes. Therefore, the desirability value of 0.75 was found for achieving the maximum removals of 90.10 and 84.70% for TOC and TN, respectively, the minimum H₂O₂ residual of 1.49 mg/L, and the maximum CH₄ yield of 58.22% at the optimum conditions for the influent TOC concentration of 626 mg/L, the feed flow rate of 45 mL/min, the inlet concentration of H₂O₂ of 350 mg/L, and the pH of 6.59. As a final point, the obtained optimal operating conditions were used in another experimental run to validate the predicted values. Consequently, the TOC removal of 91.29%, the TN removal of 86.05%, the H₂O₂ residual of 1.45%, and the maximum CH₄ yield of 55.72% were obtained experimentally, confirming the reliability of the model since all model parameters were within the 95% CI of 88.89–91.31% for TOC removal, 82.64–86.77% for TN removal, 1.42–1.56 mg/L for H₂O₂ residual, and 55.45–60.99% for CH₄ production.

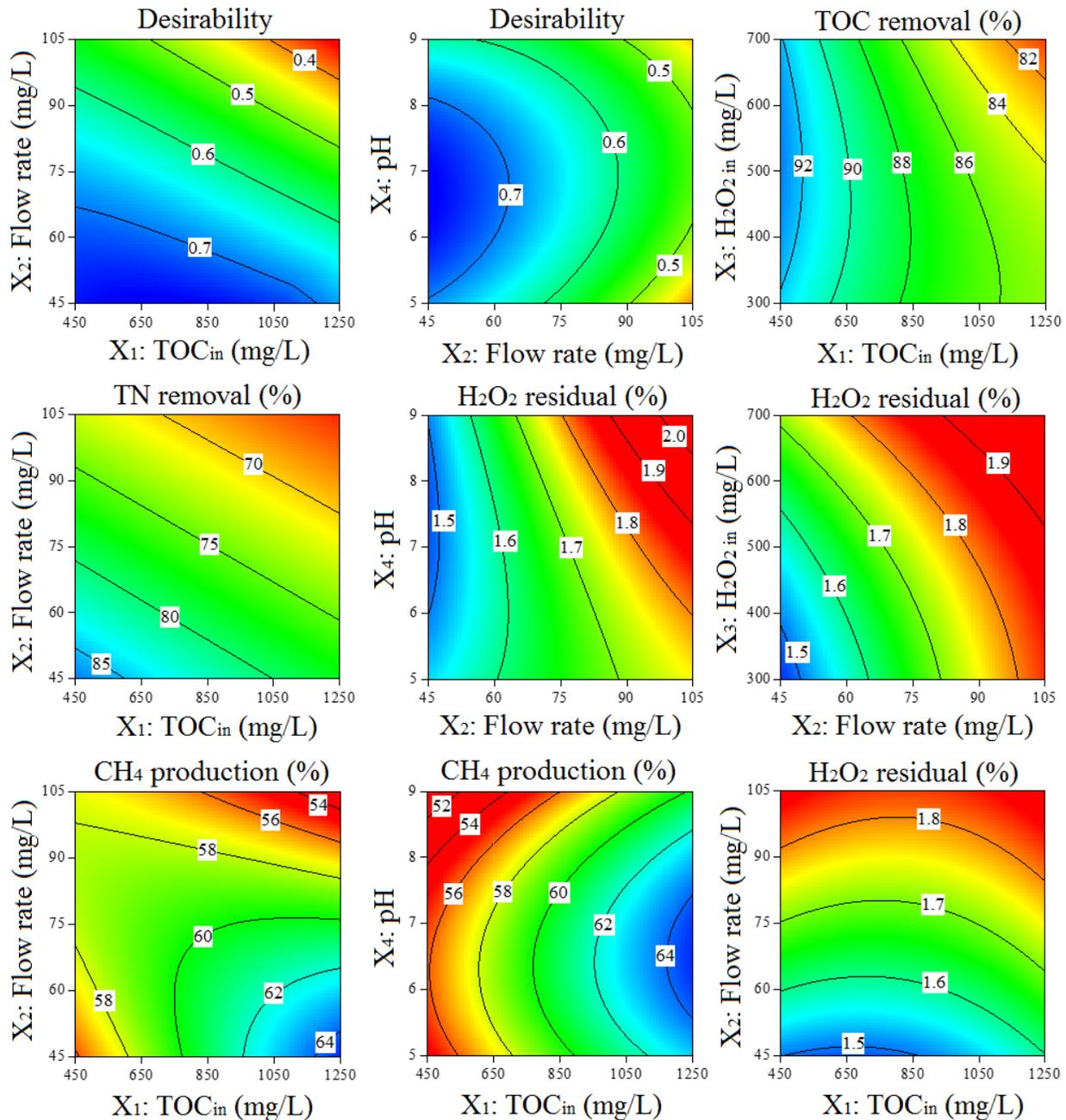


Figure 8.4. Desirability 2D plots maximizing the percentual TOC removal, TN removal, and CH₄ production while minimizing the H₂O₂ residual at optimum factor settings of influent TOC concentration of 626 mg/L, feed flow rate of 45 mL/min, inlet H₂O₂ concentration of 350 mg/L, and pH of 6.59 in the combined ABR–AS–UV/H₂O₂ processes.

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8.3.5. Analysis of reactors for the combined ABR–AS–UV/H₂O₂ processes for the actual slaughterhouse wastewater treatment

The core of this study was to analyze the integrated processes at the best operating conditions for maximum overall treatment. For designing purposes, the substrate concentrations emerging from the biological units are of a major importance. The substrate concentrations in the stream leaving the combined ABR–AS–UV/H₂O₂ system depend on parameters such as the initial TOC concentration, retention times in each reactor, including anaerobic (t_{ABR}), aerobic (t_{AS}), and UV/H₂O₂ (t_{UV}), and also the recycle ration in the photoreactor (r). Upon determining these parameters, the combined ABR–AS–UV/H₂O₂ model should be able to predict substrate concentrations in the effluent stream.

The first order rate constant in each compartment in the ABR was calculated by Equation (8.5) with a net biomass concentration in each ABR compartment of 25,000 mgVSS/L. Consequently, the equation of an ABR with five compartments (S_{ABR}) could be obtained by substitution on Equation (8.6). Thus, the overall equation for the final effluent of an ABR with five compartments at steady state without recycle (S_{ABR}) can be expressed as a function of the flow rate (Q) as shown in Equation (8.19) or as a function of the residence time in the ABR (t_{ABR}) as shown in Equation (8.20):

$$S_{ABR} = \frac{S_{in}}{(1 + 1.1589/Q)(1 + 0.2128/Q)(1 + 0.2232/Q)(1 + 0.2433/Q)(1 + 0.2486/Q)} \quad (8.19)$$

$$S_{ABR} = \frac{S_{in}}{(1 + 0.0322t_{ABR})(1 + 0.0059t_{ABR})(1 + 0.0062t_{ABR})(1 + 0.0068t_{ABR})(1 + 0.0069t_{ABR})} \quad (8.20)$$

Likewise, Equation (8.7) was used to calculate the first order rate constant in the AS reactor, considering a net biomass concentration in the AS bioreactor of 3,000 mgVSS/L. Therefore, Equation (8.7) is reduced to Equations (8.21) and (8.22) that were used to predict the effluent concentrations in the AS reactor as a function of the flow rate (Q) or as a function of the residence time in the AS (t_{AS}), respectively:

$$S_{AS} = \frac{S_{in}}{(1 + 5.0318 /Q)} \quad (8.21)$$

$$S_{AS} = \frac{S_{in}}{(1 + 0.3978 t_{AS})} \quad (8.22)$$

Besides, uniform light distribution was assumed throughout the lab-scale UV/H₂O₂ photoreactor due to the limited annular space. Thus, by employing the photon irradiation balance, the local volumetric rate of energy absorption (LVREA) could be written based on the Beer–Lambert law (Ghafoori et al., 2014a; Bustillo-Lecompte et al., 2016a), as shown below:

$$LVREA = I_o \left(\frac{\varepsilon_{H_2O_2} [H_2O_2] + \varepsilon_{HO_2^-} [HO_2^-]}{\varepsilon_{H_2O_2} [H_2O_2] + \varepsilon_{HO_2^-} [HO_2^-] + \varepsilon_{S_r} [S_r]} \right) \times \left(1 - \exp(-2.303 \ell \{ \varepsilon_{H_2O_2} [H_2O_2] + \varepsilon_{HO_2^-} [HO_2^-] + \varepsilon_{TOC} [S_r] \}) \right) \quad (8.23)$$

where the intensity of the incident light (I_o) was calculated to be 2×10^{-5} Einstein/L.s for the UV-C wavelength of 254 nm. The photon irradiance was estimated from the 14 W power input of the low pressure lamp divided by the volume of the photoreactor with a 10% attenuation from the quartz sleeve, a 33% efficiency of the low pressure lamp, and considering the portion of the UV radiation absorption by H₂O₂ (Bustillo-Lecompte et al., 2016a). Furthermore, the molar extinction coefficients of H₂O₂ ($\varepsilon_{H_2O_2}$), HO₂⁻ ($\varepsilon_{HO_2^-}$), and S_r (ε_{S_r}) were calculated to be 18.7 1/M.cm, 210.0 1/M.cm, and 132.7 1/M.cm at 254 nm, respectively, by measuring the absorbance by means of spectrophotometry at 254 nm (Bustillo-Lecompte et al., 2016a). Consequently, by substitution of Equation (8.9) into Equation (8.12) and assuming complete mineralization at steady-state conditions with a recycle ratio (r) of 0.18 (Bustillo-Lecompte et al., 2016a), Equation (8.24) could be used to predict the effluent concentrations in the UV/H₂O₂ photoreactor as a function of the flow rate (Q) and Equation (8.25) as a function of the residence time in the UV/H₂O₂ (t_{UV}), respectively.

$$S_{UV} = \frac{S_{in} \times \exp(-6.8655 / Q [1+r])}{(1+r)} \quad (8.24)$$

$$S_{UV} = \frac{S_{in} \times \exp(-4.3098 t_{UV} / [1+r])}{(1+r)} \quad (8.25)$$

Finally, for the continuous ABR–AS–UV/H₂O₂ system with recycle, Equations (8.19), (8.21), and (8.24) were combined. As a result, Equation (8.26) was used to predict the effluent concentrations of TOC for the combined ABR–AS–UV/H₂O₂ system with recycle.

$$S_r = \frac{S_{in} \times \exp(-6.8655 / Q [1+r])}{(1+r)(1+1.1589/Q)(1+0.2128/Q)(1+0.2232/Q)(1+0.2433/Q)(1+0.2486/Q)(1+5.0318/Q)} \quad (8.26)$$

The TOC represented as all substrates for the model validation since the TOC analysis is more suitable for determining organic matter content by taking into account all oxidation states while providing an accurate appraisal of the organic compounds present in a wastewater sample including intermediates or by-products in comparison to BOD or COD and without generating toxic analytical waste. The TOC analysis excludes the inorganic carbon compounds by measuring the CO₂ generated during the combustion when the organic compounds are oxidized in order to obtain more accurate results (Bustillo-Lecompte et al., 2014). The comparison between predicted and observed values for the influent concentrations of TOC, inlet H₂O₂ concentration, and pH is presented in Figures 5a to 5c, respectively. The non-linear least square function was used to determine the best-fit criterion showing an agreement between the predicted model and the experimental data. The results are also in line with previous studies (Bustillo-Lecompte et al., 2014; Bustillo-Lecompte and Mehrvar, 2015). Therefore, Equation (8.26) could be used to predict the effluent TOC concentration at a specific retention times in the combined ABR–AS–UV/H₂O₂ system with recycle.

8.3.6. Cost-effectiveness analysis

8.3.6.1. Optimization of the total retention time

For the combined ABR–AS–UV/H₂O₂ processes, different sets of retention times to reduce the TOC concentration in the effluent were evaluated as shown in Figure 8.5d. For a TOC removal higher than 80%, the smallest retention time in the combined system should be 7 h; similar values have been reported in the previous study (Bustillo-Lecompte and Mehrvar, 2015). However, the system is expected to achieve high removal efficiencies of more than 90%. Therefore, the overall retention time should be minimized to 10 h as shown in Figure 8.5d.

8.3.6.2. Optimization of the electrical energy consumption

The electrical energy consumption for each process was evaluated and its minimization was studied. In the case of the anaerobic process, the main energy consumption is coming from the pumping system as shown in Equation (8.27).

$$E_{ABR} = \frac{Q \times \rho \times g \times h}{1000 \times \eta} t_{ABR} \quad (8.27)$$

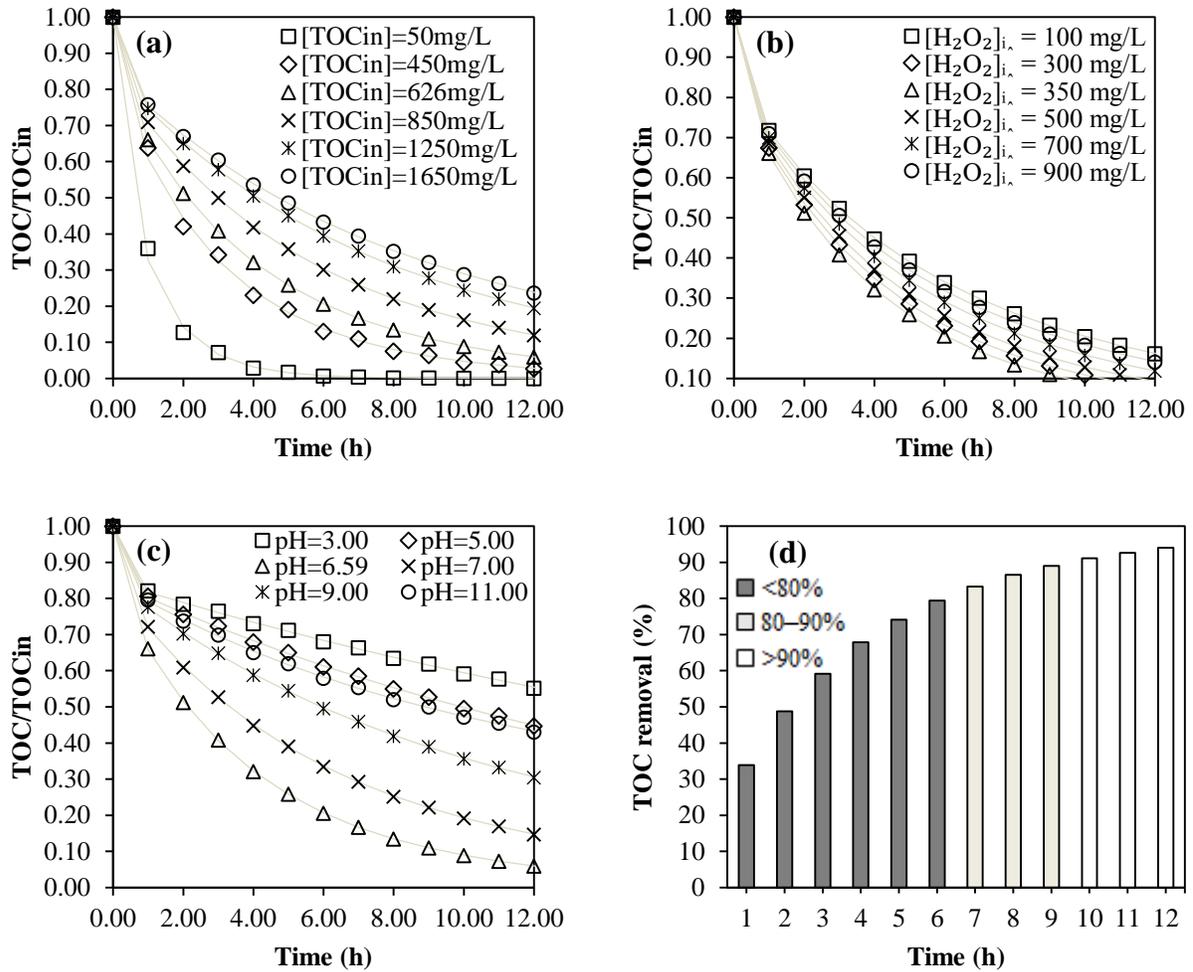


Figure 8.5. Comparison of model predictions and experimental data of TOC/TOC_{in} as a function of retention time for different (a) influent concentrations of TOC; (b) inlet H₂O₂ concentration; (c) and pH in the combined ABR-AS-UV/H₂O₂ processes; and (d) effect of retention time to reduce the TOC concentration in the actual slaughterhouse wastewater. The lines are the corresponding model predictions. Initial conditions: T=22°C, recycle rate=0.18, and optimum operating conditions of [TOC]_{in}=626 mg/L, inlet H₂O₂ concentration=350 mg/L, and pH=6.59, excepting when analyzing each effect accordingly. J. Environ. Manage. (2016), *In Press*.

where ρ , g , h , and η are the wastewater density (1000 kg/m³), gravity (9.81 m/s²), total head (0.5m), and pump efficiency (60%). Thus, the hourly energy consumption for the ABR (E_{ABR}) could be calculated by Equation (8.28) with the feed flow rate in L/s.

$$E_{ABR} = 0.0082 Q \times t_{ABR} \quad (8.28)$$

In the case of the aerobic process, the aeration power requirements were estimated from the airflow rate, discharge and inlet pressures, and air temperature. By assuming adiabatic conditions, 1.2 kg air/m³ required air mass flow rate, and inlet and outlet pressures of 0.95 and 1.56 atm, respectively, the aeration electrical power (P_{AS}) with an efficiency of 80% could be determined by Equation (8.29), where R , T , and r_{air} are the gas constant (8.314 kJ/kmole K), the inlet temperature (303 K, in this case), and a constant for the air (8.41 kg/kmole) calculated from the specific heat and the mean molecular weight of air, respectively. Thus, the hourly energy consumption for the AS bioreactor could be calculated by Equation (8.30) (Edalatmanesh et al., 2008).

$$P_{AS} = \frac{q_{air} \times R \times T}{r_{air} \eta} \left[\left(\frac{p_f}{p_{in}} \right)^{0.283} - 1 \right] \quad (8.29)$$

$$E_{AS} = 0.0671 Q \times t_{AS} \quad (8.30)$$

For the UV/H₂O₂ process, the hourly energy consumption (E_{UV}) was calculated based on the electric energy required to degrade the substrate by one order of magnitude in a unit of the actual SWW based on the rated power of the system (in this case, 0.0125 kW), as shown in Equation (8.31) (Shu et al., 2013). Thus, the energy consumption for the photoreactor to degrade 90% of the substrate could be calculated by Equation (8.32).

$$E_{UV} = \frac{P_{UV}}{\log(S_{in}/S_{UV})} t_{UV} \quad (8.31)$$

$$E_{UV} = 0.0125 t_{UV} \quad (8.32)$$

Assuming losses to be negligible; Equation (8.33) is used to determine the residence time ratio between each unit operation. Therefore, Equations (8.28) and (8.30) were modified to be in terms of

the photoreactor residence time (t_{UV}) and overall residence time (t_{Total}) for the purpose of the minimization of the residence time in each unit operation as shown in Equations (8.34) and (8.35), respectively.

$$Q = \frac{V_{Total}}{t_{Total}} = \frac{V_{ABR}}{t_{ABR}} = \frac{V_{AS}}{t_{AS}} = \frac{V_{UV}}{t_{UV}} \quad (8.33)$$

$$E_{ABR} = 0.0014 t_{ABR}/t_{UV} \quad (8.34)$$

$$E_{AS} = 0.0925 t_{AS}/t_{UV} \quad (8.35)$$

Consequently, Figure 8.6a depicts the minimum total electrical energy consumption for the combined ABR–AS–UV/H₂O₂ system by comparing each individual reactor consumption with the overall system consumption. It can be inferred that the minimum energy consumption of 0.0194 kWh is achieved with a residence time in the photoreactor of 47 min. Therefore, the residence times for the ABR and AS bioreactors are 6.82 and 2.40 h, respectively, by using the minimized overall retention time of 10 h from Figure 8.5d.

8.3.6.3. Optimization of the overall treatment cost

The costs related to installation and commissioning were not considered in this analysis because the potential users in the meat processing industry have to evaluate these costs separately in a case-by-case basis. Therefore, the power consumption was used for each process multiplied by the electricity rate. Moreover, in the case of the ABR process, an optimum CH₄ yield of 55.72% at a gas flow rate of 64 mL/min was obtained by biogas analysis (Landtec Biogas 5000, Colton, CA). These values are in line with those found in the literature for lab-scale biogas reactors (Kaparaju et al., 2009; Cadena Pereda et al., 2010; León-Becerril et al., 2016). Therefore, the total methane production can be expressed in terms of TOC degraded:

$$\frac{\text{mL } CH_4}{\text{mg } TOC_{removed}} = \frac{64 \text{ mL } CH_4 / \text{min}}{25.72 \text{ mg } TOC / \text{min}} = 2.50 \text{ mL } CH_4 / \text{mg } TOC \quad (8.36)$$

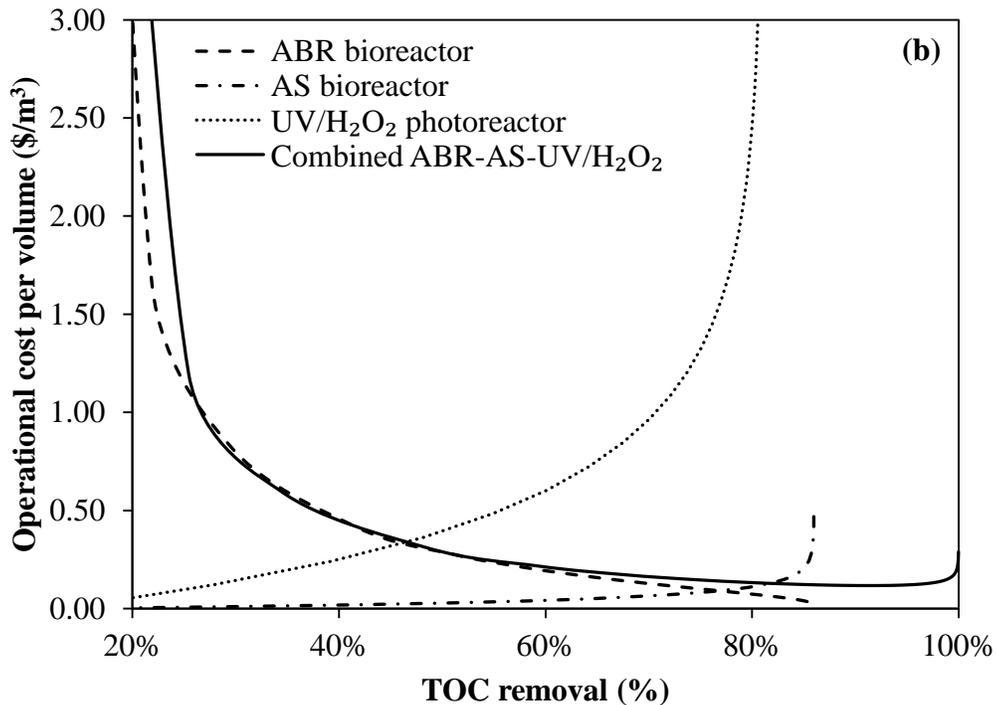
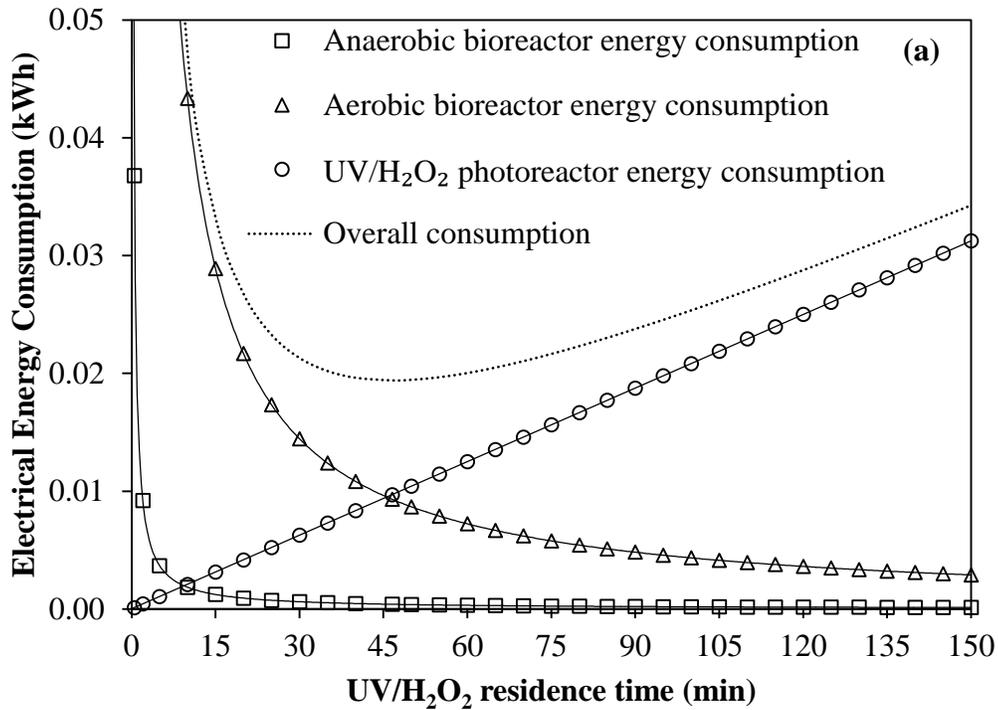


Figure 8.6. Comparison of individual ABR, AS, and UV/H₂O₂ processes with the combined ABR-AS-UV/H₂O₂ system in continuous mode with recycle: (a) Electrical energy consumption based on the residence time in the photoreactor; and (b) Operational costs per cubic meter of treated actual slaughterhouse wastewater.

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Consequently, by considering the lower heating value (LHV) of CH₄ of 35.9 MJ/m³, a daily energy generation of 0.05 kWh is obtained. According to de Mes et al. (2003), biological processes commonly require low power with energy requirements in the range 0.01–0.10 kWh/m³. In this case, 0.005 kWh and 0.02 kWh are required for the ABR process and combined ABR–AS–UV/H₂O₂ system, respectively, representing about 39% of the generated power. These numbers will be representative as a base for future studies on process optimization, modeling, and scale-up.

As a result, Figure 8.6b compares the operational costs for the individual ABR, AS, and UV/H₂O₂ processes with that of the combined ABR–AS–UV/H₂O₂ system in terms of cost per cubic meter of the treated actual SWW against the overall percentual TOC removal. A minimum overall treatment cost of 0.12 \$/m³ of actual SWW for a maximum TOC removal of 91.25% was achieved under the optimum conditions from the DOE.

It is confirmed that the overall operational costs increase with the TOC removal because of the electricity consumption, especially in the UV/H₂O₂ process alone, reaching values of up to ten times higher than those of the biological processes. In contrast, although the maximum attainable removal in the ABR was 86%, the costs have an inverse trend due to the potential energy recovery from CH₄ production; whereas, in the AS bioreactor in order to achieve removals higher than 80%, the aeration power consumption will increase the overall treatment costs. In the combined processes, the overall benefits of both biological treatment and AOPs are integrated. Thus, energy costs are offset by the on-site renewable energy from CH₄ production.

8.4. Conclusions

The optimization of combined biological treatment with advanced oxidation processes allowed achieving a highly cost-effective degradation of actual SWW with percentual removals of 91 and 86% for TOC and TN, respectively, as well as obtaining a CH₄ yield, as the percent TOC converted to CH₄, of 55.72% while having a minimum H₂O₂ residual of 1.45% in the effluent. The combined processes were then simulated and promising results were obtained when compared to each individual process. The non-linear least square function was used to determine the best-fit criterion and the comparison between predicted and experimental values showed a good agreement between the predicted model values and the experimental data.

A CEA was performed at the optimal conditions for the actual SWW treatment by optimizing the residence time, electrical energy consumption, and the overall treatment cost. The minimum total retention time was determined to be 10 h with individual residence times of 6.82 h, 2.40 h, and 47 min in the ABR, AS bioreactor, and UV/H₂O₂ photoreactor, respectively, for the minimum electrical power consumption of 0.0194 kWh. A minimum overall treatment cost of 0.12 \$/m³ of actual SWW for a maximum TOC removal of 91.25% was achieved at the optimum conditions based on the experimental design and degradation mechanism results.

Therefore, the proposed models explaining the actual slaughterhouse wastewater treatment by combined anaerobic, aerobic, and UV/H₂O₂ processes for organics removal and CH₄ production could be used as a base for future studies for the reduction of operating costs while providing high-quality treated wastewater for water reuse in the meat processing industry becoming a cost-effective alternative to conventional methods and simultaneously beneficial to the environment.

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CHAPTER 9

CONCLUSIONS AND RECOMMENDATIONS

9.1. Conclusions

The purpose of this study was to determine the current wastewater treatment technologies used in the meat processing sector in Ontario, assess possible alternatives in order to minimize the impact of the discharge of these wastewaters to the environment, optimize reactors and systems for the treatment of actual slaughterhouse wastewater, maximize overall treatment efficiency, describe common degradation mechanisms, and perform a cost-effectiveness analysis, minimizing the incurred treatment costs, the electrical energy consumption, and the retention time required for the efficient treatment of slaughterhouse effluents and potential energy recovery from combined biological and advanced oxidation processes for the treatment of actual wastewater from the meat processing sector in Ontario. The following conclusions are drawn from this dissertation:

- A summary of the most commonly applied technologies and combined processes during the last decade with particular attention to treatment efficiencies in terms of organic and nutrient removal, highlighting commonly used parameters, such as COD, TOC, BOD, and TN was developed. The treatment efficiency of SWW was found to vary extensively and depends on several factors including, but not limited to, the characteristics of the SWW, the HRT, the type of treatment, and the pollutant concentration in the influent.
- SWWs are commonly pre-treated by screening, settling, blood collection, and fat separation, followed by physicochemical treatment, DAF, coagulation/flocculation, and/or secondary biological treatment prior to discharge on the sewage system. Although the organic matter and nutrient removal achieve high efficiencies, the treated SWW effluent need further treatment by membrane technologies, AOPs, or other appropriate treatment methods as combined processes to provide high-quality treated water allowing water recycle in the meat processing industry.

- Combined processes have evolved into a reliable technology successfully used for many SWW effluents. However, the selection of a specific treatment mainly depends on the characteristics of the SWW being treated, the BAT, and the compliance with current regulations under different political jurisdictions.
- A CEA was used to determine the best alternative for SWW treatment from six different systems selected from the literature review, including individual UV/H₂O₂, AS, and ABR processes, and combined ABR-AS, AS-ABR, and ABR-AS-UV/H₂O₂ processes. The combined ABR-AS-UV/H₂O₂ processes was more technically efficient than other individual and combined processes, removing 15% more TOC during the same amount of operating time.
- The UV/H₂O₂ process alone was the least efficient technology with an optimum removal of 49.88% at a high cost of 67.06 \$/kg of TOC removed. However, it was also found that at low or intermediate TOC removal requirements, combined and individual processes are comparable in economic terms. In combined processes, the main costs are initially for pumps, reagents, and air injection. Only when the TOC removal is higher than 60%, the electricity costs increase.
- It was determined that the optimum system for the TOC removal was ABR-AS-UV/H₂O₂, with an optimal TOC removal of 92.46% at an HRT of 41 h, at a cost of 1.25 \$/kg of TOC removed and \$11.60/m³ of treated SWW. However, costs could be reduced by subtracting the electrical costs by considering potential energy recovery from anaerobic pre-treatment.
- During optimization of the combined ABR–AS system, results from the three-factor, three-level BBD to evaluate the treatment of SWW demonstrated the influent TOC concentration significant effects on all responses including percent TOC removal, TN removal, TSS residual, and biogas yield.
- The feed flow rate was also found to be significant on the percent TOC removal, TN removal, and TSS residual; whereas, the pH was found to be significant on percent TN removal and biogas yield. There was only one cross-factor interaction, between the feed flow rate and the pH, which showed no significant effect on two responses, percent TN removal and TSS residual, despite being significant on TOC removal and biogas yield simultaneously.

- On the other hand, a desirable interaction to reach maximum TOC and TN removal with minimum TSS residual was achieved when both the influent TOC concentration and the feed flow rate are minimum, for biogas yield it is necessary a high influent TOC concentration at an optimum value for the feed flow rate. Likewise, a desirable interaction to reach maximum TOC and for biogas yield was achieved when there is an optimum value for both the feed flow rate and pH.
- Maximum removals of 85.03 and 72.10% for TOC and TN, respectively, minimum TSS residual of 19.54 mg/L, and maximum biogas yield of 116.56 mL/min were found at optimum conditions. The methane production was 3.76 L/kg TOC removed, equivalent to a daily energy generation of 1.23 kWh. Consequently, the laboratory scale combined ABR-AS system could generate 0.12 \$/day. Thus, becoming a cost-effective alternative and simultaneously beneficial to the environment.
- The developed statistical models provided a detailed exploration of the simultaneous cross-factor interactive effects of the influent TOC concentration, the feed flow rate, and the pH. Therefore, the proposed models explaining slaughterhouse wastewater treatment by combined anaerobic–aerobic processes for biogas production and organics removal could be used as a base for future studies for the reduction of operating costs while providing high quality treated wastewater for water reuse in the meat processing industry.
- The individual UV/H₂O₂ process in a continuous photoreactor with recycle was studied for optimization using a four-factor, five-level CCD. Results demonstrated that the influent concentrations of TOC and H₂O₂, the flow rate, and the recycle ratio presented considerable effect on the TOC and the H₂O₂ residual.
- The cross-factor interactions of the recycle ratio with other variables, including the influent concentration of TOC, the influent H₂O₂ concentration, and the flow rate were found to have a high significant effect on both the TOC removal and the H₂O₂ residual. Thus, an optimum recycle ratio was found to be highly significant to achieve a maximum TOC removal with a minimum H₂O₂ residual for the treatment of SWW.

- A maximum TOC removal of 81% and minimum H₂O₂ residual of less than 2% were found at the optimum operating conditions of 24 mg/L influent concentration of total organic carbon, 860 mg/L influent H₂O₂ concentration, 15 mL/min flow rate, and recycle ratio of 0.18 based on the developed quadratic models and the desirability multiple response method.
- The developed mathematical models provided a detailed exploration of the simultaneous cross-factor interactive effects of the independent variables on the responses. A continuous UV/H₂O₂ photoreactor with recycle could significantly increase the removal of TOC while reducing the percent H₂O₂ residual in the effluent as a post-treatment method. Therefore, the proposed models explaining the photochemical treatment of slaughterhouse wastewater by the continuous UV/H₂O₂ photoreactor with recycle could be used as a base for future studies on process optimization, photoreactor design, modeling, and scale-up.
- The optimization of combined biological treatment with advanced oxidation processes allowed achieving a highly cost-effective degradation of actual SWW with percentual removals of 91 and 86% for TOC and TN, respectively, as well as obtaining a CH₄ yield of 55.72% while having a minimum H₂O₂ residual of 1.45% in the effluent.
- A CEA was performed at the optimal conditions for the actual SWW treatment by optimizing the residence time, electrical energy consumption, and the overall treatment cost. The minimum total retention time was determined to be 10h with individual residence times of 6.82 h, 2.40 h, and 47 min in the ABR, AS bioreactor, and UV/H₂O₂ photoreactor, respectively, for the minimum electrical power consumption of 0.0194 kWh. A minimum overall treatment cost of 0.12 \$/m³ of actual SWW for a maximum TOC removal of 91.25% was achieved at the optimum conditions based on the experimental design and degradation mechanism results.
- The proposed models explaining the actual slaughterhouse wastewater treatment by combined anaerobic, aerobic, and UV/H₂O₂ processes for organics removal and CH₄ production could be used as a base for future studies for the reduction of operating costs while providing high-quality treated wastewater for water reuse in the meat processing industry becoming a cost-effective alternative to conventional methods and simultaneously beneficial to the environment.

9.2. Recommendations

The following recommendations are suggested for further research on combined biological and AOPs processes for the treatment of actual SWW:

- Further studies should be focused on the characterization of the microorganisms present in the activated sludge to determine their nitrifying and denitrifying abilities.
- It is suggested to use different UV lamps with various intensities to compare the effect of the light intensity on actual SWW treatment since light intensity has significant effect on the photodegradation effectiveness.
- Further research should be also considered for the examination of emerging contaminants present in slaughterhouse wastewater, including pharmaceutical compounds used by veterinary physicians, anti-inflammatories, cleaning products, endocrine disruptors, and possible hazardous compounds.
- The literature review and actual SWW sampling revealed significant presence of heavy metals such as lead. Therefore, studies on the removal of heavy metals present in actual SWW should also be conducted.
- Further work should conduct the analysis of different intermediates that may be formed during the UV/H₂O₂ treatment.
- The study of the health effects associated with wastewater treatment, disposal, and reuse in the meat processing industry should be considered due to the presence of pathogens in the SWW.
- Further studies should focus on the CFD modeling for a pilot-scale combined biological and advanced oxidation system, especially in the turbulent regime where literature is scarce.
- Finally, a life-cycle assessment integrating external costs in the meat processing industry could be a valuable contribution of future studies, evaluating, inputs and outputs, greenhouse gas emissions, and the benefits from the potential energy recovery as well as water recycle and reuse.

NOMENCLATURE

c	residual term
$C_{H_2O_2in}$	hydrogen peroxide concentration in the influent
$C_{H_2O_2M}$	hydrogen peroxide concentration entering the photoreactor
$C_{H_2O_2out}$	hydrogen peroxide concentration in the effluent
C_{SWWin}	slaughterhouse wastewater concentration in the influent
C_{SWWM}	slaughterhouse wastewater concentration entering the photoreactor
C_{SWWout}	slaughterhouse wastewater concentration in the effluent
D	desirability objective function
d_i	response range i
d_1	total organic carbon removal response range
d_2	H ₂ O ₂ residual response range
df	Degrees of freedom
df_{Error}	degree of freedom of the residuals
df_{Model}	degrees of freedom for the model
E	Einstein unit
E^0	incident photon irradiance
E_r	energy rate (\$/kWh)
F	Fisher's exact test
F -value	Fisher's exact test value
F/M	food to microorganism ratio
g	gravity (9.81 m/s ²)
h	total head (m)
J	electricity cost (\$/kg)
K	first order rate coefficient of substrate
k	number of factors of the experimental design
k'	the sum of the direct photolysis rate (k_{UV}) and the indirect photolysis rate ($k_{\bullet OH}$)
$k_{\bullet OH}$	oxidation rate/indirect photolysis rate
k_1	first order rate coefficient of substrate in compartment 1 of the ABR

k_{AS}	first order rate coefficient in the AS bioreactor (L/mg.h)
k_i	first order rate coefficient of substrate in compartment i of the ABR
K_s	specific rate of light absorption of the target compound
k_{TOC}	second-order rate constants (L/mg.h)
k_{U_i}	second-order rate constants (L/mg.h)
k_{UV}	direct photolysis rate
MSS_{Model}	mean sum of squares due to the model
MSS_{Error}	mean sum of squares due to error (residuals).
N	number of independent variables
n	number of responses in the measure
p	probability coefficient
P	power rating for the system (W)
Q	flow rate (mL/min)
p -value	probability value
Q	flow rate (L/min)
r	recycle ratio
R^2	determination coefficient
R_1	reaction rate of $\cdot\text{OH}$ (mg/L.h)
R_2	reaction rate of $\cdot\text{OH}$ with TOC (mg/L.h)
R_3	reaction rate of $\cdot\text{OH}$ with a scavenger (U_i) (mg/L.h)
S_{AS}	final effluent concentration of the substrate in the AS bioreactor (mg/L)
S_f	concentration of substrate in effluent (mg/L)
S_i	concentration of substrate in compartment i of the ABR (mg/L)
S_{i-1}	concentration of substrate in compartment $i-1$ of the ABR (mg/L)
S_{in}	concentration of substrate in influent (mg/L)
S_r	concentration of substrate in the recycle per pass (mg/L)
SS_{Error}	sum of squares of the residuals
SS_{Model}	sum of squares of the model
SS_{Total}	total sum of squares
t	hydraulic retention time (h)
t_{ABR}	hydraulic retention time of the ABR process (h)
t_{AS}	hydraulic retention time of the aerobic AS process (h)
t_{UV}	hydraulic retention time of the UV/H ₂ O ₂ process (h)

U	molar photon energy (4.72×10^5 J/E at 254 nm)
U_i	a scavenger for the $\cdot\text{OH}$, where $i = a, b, \dots, n$ (mg/L)
V	total volume of reactor (L)
V_{AS}	volume of the AS bioreactor (L)
V_i	volume of compartment i of the ABR (L)
V_{ABR}	volume of the ABR (L)
V_{AS}	volume of the aerobic AS reactor (L)
V_T	treated SWW volume (L)
V_{UV}	volume of the UV photoreactor (L)
W_1	sum of the weights of the dried filter paper, dish and solids of the sample (mg)
W_2	weight of the dried filter paper (mg)
W_3	weight of the dried dish (mg)
X	biomass concentration of substrate (mg/L)
X_{AS}	biomass concentration in the AS bioreactor (mg/L)
X_i	biomass concentration of substrate in compartment i of the ABR (mg/L)
X_i	independent variable i
X_j	independent variable j
Y_i	predicted response

Greek letters

α	significance level
α	absorbance of the solution
β_o	constant coefficient of the statistical model
β_i	linear coefficients of the statistical model
β_{ii}	quadratic coefficients of the statistical model
β_{ij}	cross-factor interaction coefficients of the statistical model
ζ	constant that depends on type of AOP (mg/h.W)
ε_S	molar attenuation coefficient for the targeted substrate
ℓ	solution depth or path length
ρ	water density (1000 kg/m^3)
ϕ_{SWW}	quantum yield for the SWW
η	pump efficiency

Acronyms

2D	two-dimensional
3D	three-dimensional
ABR	anaerobic baffled reactor
AC	activated carbon
AdP	adsorption process
AeP	aerobic process
AF	anaerobic filter
AnaP	anaerobic process
ANOVA	analysis of variance
ANZECC	Australian and New Zealand Environment and Conservation Council
AOP	advanced oxidation process
APHA	American Public Health Association
AS	activated sludge
BAT	best available technology
BBD	Box-Behnken design
BOD	biochemical oxygen demand
BOD _{in}	influent concentration of biochemical oxygen demand
CC	chemical coagulation
CCD	central composite design
CEA	cost-effectiveness analysis
CEC	council of the European communities
CI	confidence intervals
CM	composite membrane
COD	chemical oxygen demand
COD _{in}	influent concentration of chemical oxygen demand
CSTR	continuous flow stirred-tank reactor
CW	constructed wetland
DAF	dissolved air flotation
DO	dissolved oxygen
DOE	design of experiments
DW	distilled water
EC	electrocoagulation

ECO	environmental commissioner of Ontario
FAU	formazin attenuation units
FTU	formazin turbidity units
GR	gamma radiation
HFCW	horizontal flow constructed wetland
HRT	hydraulic retention time
IR	internal recycle
LVREA	local volumetric rate of energy absorption
MBR	membrane bioreactor
MF	microfiltration
OEB	Ontario energy board
OLR	organic loading rates
OMAFRA	Ontario Ministry of Agricultural and Rural Affairs
PACl	Polyaluminum chloride
RO	reverse osmosis
RSM	response surface methodology
SBR	sequencing batch reactor
SS	sum of squares
SWW	slaughterhouse wastewater
TKN	total Kjeldahl nitrogen
TN	total nitrogen
TN _{in}	influent concentration of total nitrogen
TOC	total organic carbon
TOC _{in}	influent concentration of total organic carbon
TSS	total suspended solids
UAF	up-flow anaerobic filter
UAPF	up-flow anaerobic packed-bed filters
UF	ultrafiltration
UV/H ₂ O ₂	ultraviolet light and hydrogen peroxide
US EPA	United States Environmental Protection Agency
VFCW	vertical flow constructed wetlands
VSS	volatile suspended solids
VUV	vacuum-ultraviolet light

APPENDICES

Appendix A. Abstract reprint from Journal of Environmental Management 161 (2015) 287-302, with permission from Elsevier. License Number 3830960007849.

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Review

Slaughterhouse wastewater characteristics, treatment, and management in the meat processing industry: A review on trends and advances



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ABSTRACT

A thorough review of advancement in slaughterhouse wastewater (SWW) characteristics, treatment, and management in the meat processing industry is presented. This study also provides a general review of the environmental impacts, health effects, and regulatory frameworks relevant to the SWW management. A significant progress in high-rate anaerobic treatment, nutrient removal, advanced oxidation processes (AOPs), and the combination of biological treatment and AOPs for SWW treatment is highlighted. The treatment processes are described and few examples of their applications are given. Conversely, few advances are accounted in terms of waste minimization and water use reduction, reuse, and recycle in slaughterhouses, which may offer new alternatives for cost-effective waste management. An overview of the most frequently applied technologies and combined processes for organic and nutrient removal during the last decade is also summarized. Several types of individual and combined processes have been used for the SWW treatment. Nevertheless, the selection of a particular technology depends on the characteristics of the wastewater, the available technology, and the compliance with regulations. This review facilitates a better understanding of current difficulties that can be found during production and management of the SWW, including treatment and characteristics of the final effluent.

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1. Introduction

The increasing growth of world population has augmented the pollution of freshwater due to the inadequate discharge of wastewater, especially in developing countries (US EPA, 2004; Leitão et al., 2006; Gopala Krishna et al., 2009; Feng et al., 2009). For this reason, water and wastewater treatment has become crucial for the continuing development of the society. Moreover, the progressively stricter standards for effluent discharge worldwide have made the developing of advanced wastewater treatment technologies necessary (Environment Canada, 2000, 2012; US EPA, 2004; World Bank Group, 2007). Besides, the continuing decreasing availability of freshwater resources has rearranged the objectives in the wastewater treatment field from disposal to reuse and recycling. As a result, a high level of treatment efficiency has to be achieved. Given the differences in location, economic resources,

living standards of different countries, and characteristics of water and its pollutants, many nations adopt diverse techniques for water and wastewater treatment (Daigger, 2009).

The meat processing sector produces large volumes of slaughterhouse wastewater (SWW) due to the slaughtering of animals and cleaning of the slaughterhouse facilities and meat processing plants (MPPs). The meat processing industry uses 24% of the total freshwater consumed by the food and beverage industry (Table 1) and up to 29% of that consumed by the agricultural sector worldwide (Mekonnen and Hoekstra, 2012; Gerbens-Leenes et al., 2013). SWW composition varies significantly depending on the diverse industrial processes and specific water demand (Matsumura and Mierzwa, 2008; Debik and Coskun, 2009; Bustillo-Lecompte et al., 2013, 2014). Slaughterhouses are part of a large industry, which is common to numerous countries worldwide where meat is an important part of their diet. Therefore, SWWs require significant treatment for a safe and sustainable release to the environment (Johns, 1995). Nevertheless, review articles on SWW and the meat processing industry are not widely available (Bull et al., 1982; Tritt and Schuchardt, 1992; Johns, 1995; Salminen and Rintala, 2002;

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Cost-effectiveness analysis of TOC removal from slaughterhouse wastewater using combined anaerobic–aerobic and UV/H₂O₂ processes



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ABSTRACT

The objective of this study is to evaluate the operating costs of treating slaughterhouse wastewater (SWW) using combined biological and advanced oxidation processes (AOPs). This study compares the performance and the treatment capability of an anaerobic baffled reactor (ABR), an aerated completely mixed activated sludge reactor (AS), and a UV/H₂O₂ process, as well as their combination for the removal of the total organic carbon (TOC). Overall efficiencies are found to be up to 75.22, 89.47, 94.53, 96.10, 96.36, and 99.98% for the UV/H₂O₂, ABR, AS, combined AS–ABR, combined ABR–AS, and combined ABR–AS–UV/H₂O₂ processes, respectively. Due to the consumption of electrical energy and reagents, operating costs are calculated at optimal conditions of each process. A cost-effectiveness analysis (CEA) is performed at optimal conditions for the SWW treatment by optimizing the total electricity cost, H₂O₂ consumption, and hydraulic retention time (HRT). The combined ABR–AS–UV/H₂O₂ processes have an optimal TOC removal of 92.46% at an HRT of 41 h, a cost of \$1.25/kg of TOC removed, and \$11.60/m³ of treated SWW. This process reaches a maximum TOC removal of 99% in 76.5 h with an estimated cost of \$2.19/kg TOC removal and \$21.65/m³ treated SWW, equivalent to \$6.79/m³ day.

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1. Introduction

Slaughterhouse wastewater (SWW) is considered detrimental worldwide due to its composition, characterized mostly by a complex mixture of fats, proteins, and fibers (Johns, 1995; Muñoz, 2005). Wastewaters from slaughterhouses and meat processing plants (MPPs) have been considered as an industrial wastewater in the category of agricultural and food industries (Seif and Moursy, 2001). It has been classified as one of the most harmful wastewaters to the environment by the United States Environmental Protection Agency (US EPA, 2004). The effluent discharge from slaughterhouses causes deoxygenation of rivers (Quinn and McFarlane, 1989) and contamination of groundwater (Masse and Masse, 2000a).

The organic matter concentration in SWW is usually high and the residues are moderately solubilized, leading to a highly polluting effect (Ruiz et al., 1997). They usually contain high levels

of organics, pathogenic and non-pathogenic viruses and bacteria, and detergents and disinfectants used for cleaning activities (Debik and Coskun, 2009). High concentrations of biochemical oxygen demand (BOD), chemical oxygen demand (COD), total organic carbon (TOC), total nitrogen (TN), and total suspended solids (TSS) in SWW containing flesh and blood have been reported to be 4635, 15,900, 1200, 841, and 2800 mg/L or more, respectively (Tritt and Schuchardt, 1992; Masse and Masse, 2000b). Several studies have described the common characteristics of SWW (Garipey et al., 1989; Seif and Moursy, 2001; Cao and Mehrvar, 2011; Wu and Mittal, 2011; Barrera et al., 2012; Bustillo-Lecompte et al., 2013). These characteristics are summarized in Table 1, in which their common ranges and averages of COD, TOC, BOD, TSS, TN, and pH for SWW are presented.

Commonly, research on wastewater treatment includes the study of different contaminants, the effects of operating variables, and the efficiency of the processes. Nevertheless, there are limited studies on the economic information and analysis, reaction mechanisms, and kinetic modeling that may help to estimate the costs of different technologies for scale-up and industrial applications (Durán et al., 2012; Benedetti et al., 2013; Ghafouri et al., 2012, 2013, 2014).

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Photochemical degradation of an actual slaughterhouse wastewater by continuous UV/H₂O₂ photoreactor with recycle



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ABSTRACT

Slaughterhouse wastewater is treated using the UV/H₂O₂ process in a continuous photoreactor with recycle, in which the effect of the recycle ratio (the ratio of recycle flow rate to the main feed flow rate) on the photoreactor efficiency is investigated. A four-factor, five-level central composite design along with response surface methodology is used to maximize the total organic carbon removal from an actual slaughterhouse wastewater and minimize the H₂O₂ residual in the effluent. The effects of the flow rate and the influent concentrations of total organic carbon and H₂O₂ on the photodegradation of the actual slaughterhouse wastewater are also investigated. Statistical models are developed to predict both the total organic carbon removal and the H₂O₂ residual as response variables. The recycle ratio is found to be significant in minimizing the H₂O₂ residual and the cross-factor interactions of recycle ratio with other variables demonstrate a significant effect on both total organic carbon removal and H₂O₂ residual. A maximum total organic carbon removal of 81% and a minimum H₂O₂ residual of less than 2% are found at optimum operating conditions of 24 mg/L influent total organic carbon, 860 mg/L influent H₂O₂ concentration, 15 mL/min flow rate, and 0.18 recycle ratio. The model is validated under optimal operating conditions based on the experimental design results. The good agreement between model predictions and experimental values indicates that the proposed model could successfully describe the photochemical treatment of actual slaughterhouse wastewater by the continuous UV/H₂O₂ process with recycle and its applicability as a post-treatment method.

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1. Introduction

The global production of beef, pork, and poultry meat has been doubled in the past decade and is projected to steadily grow until 2050. Furthermore, the number of slaughterhouse facilities are increasing, which results in an expected higher volume of slaughterhouse wastewater (SWW) to be treated. The SWW is typically assessed in terms of bulk parameters because of the diverse pollutant loads in the SWW derived from the type and number of animals slaughtered that fluctuate amid the meat industry [1]. SWW usually contain high levels of organics and nutrients, expressed as bulk components such as biochemical oxygen demand (BOD), chemical oxygen demand (COD), and total organic carbon (TOC). Thus, SWW is considered detrimental worldwide, and on-site treatment would be the best option to treat

and disinfect the effluents to be discharged safely into receiving waters [1–5].

Advanced oxidation processes (AOPs) are becoming an attractive alternative over conventional treatment and a complimentary treatment option, as either pretreatment or post-treatment, to current biological processes for SWW treatment [3–9]. Furthermore, AOPs may inactivate microorganisms without adding additional chemicals to the SWW, avoiding the formation of hazardous by-products [6–10].

Several AOPs have been tested for SWW treatment including ozonation, gamma radiation, and UV/H₂O₂ [5–12]. However, the UV/H₂O₂ process has been found to be more efficient for SWW treatment. The UV/H₂O₂ process is five times faster in inactivation and inhibition of microorganisms as well as in degrading aromatic compounds than those of other technologies. Removal efficiencies of up to 97, 95, and 75% could be achieved by the UV/H₂O₂ process for COD, BOD, and TOC, respectively [3–9]. Thus, AOPs might be considered to enhance the SWW quality for water reuse purposes.

On the other hand, AOPs are considered multifactor systems due to the interaction of several parameters including organics

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Slaughterhouse Wastewater Characterization and Treatment: An Economic and Public Health Necessity of the Meat Processing Industry in Ontario, Canada

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Abstract

The characteristics of the slaughterhouse effluents and current wastewater treatment practices in the province of Ontario, Canada are analyzed. Meat processing plants are found to produce large amounts of wastewater due to the slaughtering process and cleaning of their facilities. Furthermore, the composition of the wastewater varies according to the type and number of animals slaughtered and the water requirements of the process. However, the slaughterhouse wastewater usually contains high levels of organics and nutrients. Several slaughterhouses in Ontario discharge their wastewater into the municipal sewer system after primary pretreatment at the meat processing plant. Therefore, due to the high-strength characteristics of the slaughterhouse effluents, an extensive treatment for a safe discharge into the environment is required. Thus, the combination of biological processes and advanced oxidation technologies for slaughterhouse wastewater treatment is evaluated in this study. Results show that the application of combined biological and advanced oxidation processes is recommended for on-site slaughterhouse wastewater treatment.

Keywords

Slaughterhouse Wastewater, Anaerobic Digestion, Activated Sludge, Advanced Oxidation Processes

1. Introduction

The treatment of water and wastewater has become crucial due to the continuous growth of world population

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Research article

Treatment of an actual slaughterhouse wastewater by integration of biological and advanced oxidation processes: Modeling, optimization, and cost-effectiveness analysis



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ABSTRACT

Biological and advanced oxidation processes are combined to treat an actual slaughterhouse wastewater (SWW) by a sequence of an anaerobic baffled reactor, an aerobic activated sludge reactor, and a UV/H₂O₂ photoreactor with recycle in continuous mode at laboratory scale. In the first part of this study, a quadratic modeling along with response surface methodology is used for the statistical analysis and optimization of the combined process. The effects of the influent total organic carbon (TOC) concentration, the flow rate, the pH, the inlet H₂O₂ concentration, and their interaction on the overall treatment efficiency, CH₄ yield, and H₂O₂ residual in the effluent of photoreactor are investigated. The models are validated at different operating conditions using experimental data. Maximum TOC and total nitrogen (TN) removals of 91.29 and 86.05%, maximum CH₄ yield of 55.72%, and minimum H₂O₂ residual of 1.45% at the photoreactor effluent were found to be optimal conditions. In the second part of this study, continuous distribution kinetics is applied to establish a mathematical model for the degradation of SWW as a function of time. The agreement between model predictions and experimental values indicates that the proposed model could describe the performance of the combined anaerobic–aerobic–UV/H₂O₂ processes for the SWW treatment. In the final part of the study, the optimized combined anaerobic–aerobic–UV/H₂O₂ processes with recycle were evaluated using a cost-effectiveness analysis to minimize the retention time, the electrical energy consumption, and the overall incurred treatment costs required for the efficient treatment of slaughterhouse wastewater effluents.

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1. Introduction

Slaughterhouse wastewater (SWW) effluents are becoming one of the major agribusiness concerns because of the elevated amounts of water used during slaughtering, processing, and cleaning of the abattoir facilities. Although physical, chemical, and biological treatment can be used for SWW degradation, each treatment process has different benefits and drawbacks depending on the SWW characteristics, best available technology, jurisdictions, and regulations (Tabrizi and Mehrvar, 2004; Barrera et al., 2012; Franke-Whittle and Insam, 2013; Bustillo-Lecompte and Mehrvar, 2015; Valta et al., 2015; Bustillo-Lecompte et al., 2015, 2016a, 2016b). However, adopting combined processes for SWW

treatment is considered operationally and economically advantageous because it incorporates and optimizes the advantages of different technologies to achieve high-quality effluents from industrial and high-strength wastewaters (Kurian et al., 2006; Mehrvar and Tabrizi, 2006; De Nardi et al., 2011; Bustillo-Lecompte et al., 2013, 2014; Bustillo-Lecompte and Mehrvar, 2015; Mowla et al., 2014).

Anaerobic treatment is the preferred biological treatment because of its effectiveness in treating high-strength wastewater such as SWW with less complex equipment requirements. Nevertheless, anaerobically treated effluents of SWW require post-treatment to comply with required discharge limits (Cao and Mehrvar, 2011; Bustillo-Lecompte et al., 2013, 2014). Therefore, aerobic treatment systems are more frequently used in wastewater treatment since they operate at higher rates than conventional anaerobic treatment methods in the case of lower strength wastewaters. Taking into account that oxygen requirements and

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Appendix F. Provincially licensed meat plants in Ontario.

(Adopted from OMAFRA, 2016).

Plant Name	Address	City	Postal Code	Website	E-mail	Fax
A.S. Poultry	7611 Kimbo Road	Smithville	L0R 2A0			
Abate Packers	7597 Jones Baseline	Arthur	N0G 1A0	http://www.abatepackers.com/	info@abatepackers.com	519-848-2793
Abattoir Brisson Ltd	1100 St. André	Embrun	K0A 1W0			
Abattoir LeFaivre	122 County Rd 15	Lefaivre	K0B 1J0			
Abattoir LeFaivre Meat	2100 Cholette St	Lefaivre	K0B 1J0			613-524-5371
Abattoir LeFaivre Meat & Slaughterhouse	2123 Joseph St, Lefaivre	Alfred	K0B 1A0			
Agram 2005 Meats Inc.	10676 Trafalgar Road	Georgetown	L7G 4S5	http://www.agrammeats.com/		905-877-5120
Al Madina Halal Meat Packers	3944 Carman Road	Brinston	K0E 1C0			
Al Madina Halal Meat Packers	2875 Lawrence Ave E	Toronto	M1P 2S8		babowath@hotmail.com	
Al Madina Halal Meat Packers	799 Brimley Rd	Toronto	M1J 1C9			
Aman's Abattoir	286 Main Street, PO Box 177	Wellington	K0K 3L0	http://www.amansabattoir.com/		
Amos Weber	556 Birch Lake Road, RR 3	Massey	P0P 1P0			
Amos Weber	405 Erb St W	Waterloo	N2L 1W7			
Athens Meat Packers	63 Addison Road	Athens	K0E 1B0			613-924-0958
Bachert Meats Inc. (2006)	43181 Blyth Road, RR 1	Walton	N0K 1Z0			519-887-9971
Barron Poultry Limited	7470 Essex County Road 18	Amherstburg	N9V 2Y7			519-726-6839
Bearbrook Farm Abattoir	5070 Herbert Drive	Navan	K4B 1J1			
Bearbrook Farm Abattoir	8411 Russell Road, RR3	Navan	K4B 1J1			
Bearbrook Games Meats Inc	5396 Dunning Rd	Navan	K4B 1J1	http://bearbrookgame meats.com/	info@bearbrookfarm.com	
Beeton Meats	233 Patterson Street North, PO Box 208	Beeton	L0G 1A0			705-458-4630
Belle Vallé Meats and Abattoir	982125 Belle Valle Road	Belle Valle New	P0J 1M0			705-563-2403
Belle Vallé Meats and Abattoir	6 Concession Casey TWSP	Liskeard	P0J 1P0			
Bennett Abattoir	1984 Hwy, 572	Ramore	P0K 1R0			
Bennett Abattoir	2 Con Hislop	Ramore	P0K 1R0			
Bentinck Packers Limited	381488 Concession 4					
Bentinck Packers Limited	NDR, RR 3	Hanover	N4N 3B9	http://www.bentinckpackers.ca/	* Use the website	519-364-0898
Berube Poultry	10135 McIntyre Road RR3	Mountain Clarence	K0E 1S0			613-989-2020
Bilal Farms Inc.	1924 Landry St	Creek	K0N 1N0	http://www.bilalfarms.com/	wzazay@hotmail.com	
Bilal Farms Inc.	47 Farmfield Crescent	Kanata	K2M 2S8			
Bill's Turkey Farm Ltd.	2978 Holborn Rd.	Queensville	L0G 1R0	http://www.billsturkeyfarm.com/		
Bismillah Halal Meats	3176 Ridgeway Drive	Mississauga	L5L 5S6			
Bismillah Meats	3900 Elginfield Road	Parkhill	N0M 2K0			
Bismillah Meat Market	1725 Kingston Rd	Pickering	L1V 4L9			

Plant Name	Address	City	Postal Code	Website	E-mail	Fax
Blackwater Meats	1255 Durham Road 13 3472 Waterworks Rd, RR 1	Sunderland	L0C 1H0			519-864-4030
Bluewater Beef	1	Mooretown	N0N 1M0	http://www.bluewaterbeef.com/	info@bluewaterbeef.com	
Bluewater Beef	2873 Kimball Rd	Courtright	N0N 1M0	ralphandbrenda@bluewaterbeef.com	murrayandsandi@bluewaterbeef.com	
Brennan Poultry	7109 Mosside Line	Alvinston	N0N 1A0	http://brennanpoultry.com/	brennanpoultry@msn.ca	613-377-1520
Brian Quinn's Meat Ltd.	3987 County Rd. #1, RR 2	Yarker	K0K 3N0	http://www.quinnsmeats.com/	* Use the website	
Buchler Farms and Abattoir	186 Horner Rd.	Magnetawan	P0A 1P0			
Cargill Foods Toronto	71 Rexdale Blvd	Toronto	M9W 1P1			519-823-5451
Cargill Meat Solutions	165 Dunlop Drive	Guelph	N1L 1P4	http://www.cargill.ca/	rick_mcclure@cargill.com	
Cargill Meat Solutions	180 Watson Pkwy S	Guelph	N1L 1P4	http://www.cargill.ca/	customer.care@betterbeef.ca	
Cedarview Farms	3028 Kimball Rd	Courtright	N0N 1H0	http://www.cedarviewfarms.org/	info@cedarviewfarms.org	
Champagne Poultry Inc.	18-30 Titan Rd	Toronto	M8Z 5Y2	http://goo.gl/7IM4Lz	http://goo.gl/iR5VrV	416-233-3067
Charles Quality Meats	1448 Wilby Road, RR 1	Wilmot	N0B 2L0			519-747-3663
Charles Quality Meats	1476 Wilby Rd.	St. Agatha	N0B 2L0			
Charlies Meats	61 Skagway Ave	Toronto	M1M 3T9	http://www.charliesmeat.com/	info@charliesmeat.com	416-261-2267
Clement Poultry & Sons	85 Lovekin Road, RR8 134 Old Milford Rd, RR 9,	Newcastle	L1B 1L9	-	webmaster@charliesmeat.com	
Cole Bros. Meat Processing	PO Box 538	Picton	K0K 2T0			
Cornell Meats	7086 Pack Road	London	N6P 1M1			
Corsetti Meat Packer Limited	2255 St Clair Ave W	Toronto	M6N 1K8			416-762-4465
Country Meadow Meats	122242 Sideroad 12, RR 3	Owen Sound	N4K 5N5	http://www.countrymeadowmeats.com/	pondwillow@bmts.com	
Country Meat Packing Ltd (CMP Meats)	1188 Hwy 8, RR 1	Dundas	L9H 5E1	http://www.countrymeatpacking.com/	albert@countrymeatpacking.com	519-622-5306
Country Meat Packing Ltd (CMP Meats)	2255 St Clair Ave W	Toronto	M6N 1K8	tony@countrymeatpacking.com	ron@countrymeatpacking.com	
Country Poultry Processing	7707 Fourth Line, RR 2	Wallenstein	N0B 2S0			
Country Poultry Processing	7705 Fourth Line	Wallenstein	N0B 2A0			
Creative Meats	7437 Hwy 17 East, RR 1	Warren	P0H 2N0		creative_meats@hotmail.com	705-967-2643
CRO Quail Farms Inc.	3625 Sixteen Road	St. Ann's	L0R 1Y0	http://www.croquail.com/contact.htm	croquail@gmail.com	905-562-6999
Dean Butcher Shop	30 Dean Park Rd 1 Queen Street, PO Box	Toronto	M1B 5S6			
Desormeaux Meats Incorporated	112	Crysler	K0A 1R0		jeanguydesormeaux@gmail.com	
Dickenson Farms	3383 Oil Springs Line 7396 W Garafraxa 3rd	Brigden	N0N 1B0	http://www.dickensonfarms.com/	joe@dickensonfarms.com	
Domingos Meat Packers Ltd.	Line, RR 3	Arthur	N0G 1A0	http://www.domingosmeatpackers.com/	company@domingosmeatpackers.com	519-848-5884
Doug's Meats	Concession Road 10, RR 3 78 Hwy, 10210 McCreary	Schomberg	LOG 1T0			
Dresden Meat Packers Limited	Line, RR 2	Dresden	N0P 1M0	http://www.dresdenmeatpackers.com/	* Use the website	519-683-4558
Dresden Meat Packers Limited	195 PK St	Dresden	N0P 1M0			
Dundalk Poultry Processing	126815 Southgate Road 12	Dundalk	N0C 1B0			
Dundalk Poultry Processing	126715 Southgate Road 12	Dundalk	N0C 1B0			
Dundalk Poultry Processing	126715 Conc 8	Dundalk	N0C 1B0			

Plant Name	Address	City	Postal Code	Website	E-mail	Fax
Elora Road Meats	598 Elora Road, RR 1 6424 8Th Line W, RR 1, Pilkington	Mildmay	N0G 2J0	http://www.eloraroadmeats.ca/	eloraroadmeats@wightman.ca	519-846- 9553
ENS Poultry Inc. Everspring Farms Ltd. (Functional Food Production Facility)	91 Railway Street 22370 Adelaide Street North, RR 3	Elora	N0B 1S0	http://www.everspringfarms.ca/contact	* Use the website	519-527- 2726
Everspring Farms Ltd. (Main Office) Ewedell Farms	1282 Oriole Park Drive	Ilderton	N0M 2A0	http://www.ewedell.ca/	info@ewedell.ca	519-659- 3043
Filicetti Foods Inc Fiore Game Farm Fiore Game Farm	350 Gayray Dr 7255 Highway 9, RR 1 165 Main St 3821 Mandaumin Rd, RR 4	Toronto Schomberg King	M9L 1P5 L0G 1T0 L0G 1T0	http://www.filicetti.com/	sales@filicetti.com	416-743- 3555
Franz Turkey Farms Ltd Franz Turkey Farms Ltd Gerald Gemus & Sons Ltd.	2950 Plank Rd 6130 Snake Lane 643 Hwy 77, RR 5, Stn Main	Petrolia Petrolia Oldcastle	N0N 1R0 N0N 1R0 N0R 1L0	http://www.franzturkeyfarms.com/	franzturkeys@hotmail.com	519-326- 3809
Gord's Abattoir Ltd.		Leamington	N8H 3V8	http://goo.gl/kFv98L	* Use the website	519-357- 3846
Green's Meat Market and Abattoir Ltd.	237 Arthur Street, RR 2 5 Rd Sideroad 41A, RR1, PO Box 414014	Wingham	N0G 2W0		gmm@bellnet.ca	
Grey County Meats Griffiths Country Meats Hafiz Halal Poultry Inc	60 Griffiths Road 116 Bloor Street East	Maxwell Oxdrift Oshawa	N0C 1J0 P0V 2J0 L1H 3M2		cmills@bmts.com	
Hank Dekoning Limited	1768 Ontario 6	Port Dover	N0A 1N1	http://goo.gl/rQKyCT	* Use the website	519-583- 0119
Hank Dekoning Limited Hank Dekoning Limited	1768 Hwy 6, RR 1 1768 Hwy 6 S, RR 3	Port Dover Port Dover	N0A 1N3 N0A 1N0			519-583- 1341
Hanson Meats Hanson Meats	4643 Highway 3, RR 4 935 Hwy 3, RR 4	Cayuga Cayuga	N0A 1E0 N0A 1E0	http://goo.gl/htmqCB	* Use the website	905-772- 4694
Harriston Packing Co. Ltd. Hastings County Meat Packers Inc	142 Arthur Street 570 Moira Rd, RR 2	Harriston Stirling	N0G 1Z0 K0K 3E0	http://www.harristonpacking.ca/	* Use the website	519-338- 3525
Hay's Custom Cutting	2958 4th Line, RR 5	Campbellford	K0L 1L0	http://www.hayscustomcutting.com/	* Use the website	705-653- 5690
Heritage Cattle Company Highgate Tender Meats Ltd.	1472 Heritage Line, RR 1 14680 Hastings Line	Keene Highgate	K0L 2G0 N0P 1T0	http://www.heritagenaturalbeef.com/ http://www.highgatetendermeats.com/	orders@heritagebeef.ca * Use the website	705-742- 0118
Highland Packers Ltd.	432 Highland Road East 1948 7th Line, Asphodel, RR 3	Stoney Creek	L8J 3G4	http://www.highlandpackers.com/	info@highlandpackers.com	905-662- 8857
Hilts Butcher Shop Ltd. Hiview Packers	RR 1 Con 7 E Pt Lot 27, Farm #335424	Norwood Dundalk	K0L 2V0 N0C 1B0			519-925- 1808
Horizon Meat Packers Inc. Hornblower Homestead & Orchard	7567 Ridge Rd, RR 3 1834 Hutchinson Road, RR 8	Shelburne Thedford	L0N 1S5 N0M 2N0	http://hornblowerhomestead.webs.com/	hornblowerhomestead@yahoo.com	905-774- 8511
Hunters Dressed Meats Ideal Meat Packers Ltd. International Food Centre Ltd	Stn Main, RR 4 1415 Bloor St W	Dunnville Owen Sound Toronto	N1A 2W7 N4K 5N6 M6P 3L4	http://huntersmeats.com/	info@huntersmeats.com	

Plant Name	Address	City	Postal Code	Website	E-mail	Fax
International Food Centre Ltd	1415 Bloor St W	Owen Sound	N4K 5N6			
International Food Centre Ltd	3570 Wolfedale Rd	Mississauga	L5C 2V6			
J Meat Distributing Inc.	14600 Concession Rd 10	Nobleton	L0G 1N0	http://goo.gl/j3bNQw	* Use the website	416-425-3792
J Meat Distributing Inc.	14600 Concession Rd 10,					
J.R. Meats	RR 3	Schomberg	L0G 1T0			
J.R. Meats	275 Frankford Road, RR 1	Foxboro	K0K 2B0			
J.R. Meats	C.P. 28 - 113 Rue					
Joe Savage & Fils Abattoir Inc.	Principale	St-Albert	K0A 3C0			
Joe Savage & Fils Abattoir Inc.	1461 Route 900 West	St-Albert	K0A 3C0		benoitsavage@hotmail.com	
Joe Savage & Fils Abattoir Inc.	49801 Glen Colin Line,					519-773-9508
Johnson Meats	RR 4	Aylmer	N5H 2R3			905-957-5986
Julius Meat Packers Inc.	2340 Patterson Road, RR 1	St. Ann's	L0R 1Y0			
Kam Li Food Co Ltd	229 Broadview Ave	Toronto	M4M 2G7			
KC Meat International Import Brokers (1243275 Ontario Inc)	33 Terry Dr	Toronto	M6N 3T4			416-769-7961
KC Meat International Import Brokers (1243275 Ontario Inc)	18347 Warden Avenue,					
King Capon Ltd.	Box 353	Sharon	L0G 1V0	http://www.kingcapon.com/	* Use the website	
King Cole Ducks Ltd.	15336 Warden Avenue	Stouffville	L4G 3H3	http://www.kingcoleducks.com/	mmoerat@kingcoleducks.com	
King Cole Ducks Ltd.	15351 Warden Avenue	Newmarket	L3Y4W1	http://www.kingcoleducks.com/	pthompson@kingcoleducks.com	905-836-4440
King Cole Ducks Ltd.	15336 Warden Avenue	Newmarket	L3Y4W1	dconzelmann@kingcoleducks.com	rgrant@kingcoleducks.com	
Kingma Meat Products Limited	1150 Regional Road 27, RR 2	St. Ann's	L0R 1Y0			
Kingma Meat Products Limited						416-441-3386
Kretschmar Inc	71 Curlew Drive	Toronto	M3A2P8	http://www.kretschmar.com/	info@kretschmar.com	613-675-2900
L'Original Packing Ltd	2567 Route 17	L'Original	K0B 1K0	http://www.loriginalpacking.ca/	general@loriginalpacking.ca	
L & M Meat Distributing	5814 Minielly Road, RR 2,			christine@loriginalpacking.ca	order@loriginalpacking.ca	
L & M Meat Distributing	PO Box 268	Wyoming	N0N 1T0	http://www.landmmeats.com/	contact@landmmeats.com	
Laplane Poultry Farms Ltd	3105 Dunning Rd	Ottawa	K4B 1J1			
Laplane Poultry Farms Ltd/Ferme Avicole Laplane Ltée	17141 Rombough Road	Monkland	K0C 1V0			
Laplane Poultry Farms Ltd/Ferme Avicole Laplane Ltée						705-328-9100
Len & Patti Butcher Block	2133 Little Britain Road	Lindsay	K9V 4R2			
Lena's Lamb	2627 McCallum Line	Wilkesport	N0P 2R0	http://www.lenaslamb.com/	lenaslamb@gmail.com	
Lindsay Zabiha Meat Packer	S 1255 Durham Road #13	Sunderland	L0C 1H0			
Lindsay Zabiha Meat Packer	1094 Danforth Ave	Toronto	M4J 1M2			
Little Britain Meat Packers (2012)	917 Little Britain Rd, RR 2	Little Britain	K0M 2C0	http://littlebritainmeatpackers.com/	vgreco@littlebritainmeatpackers.com	705-786-9972
Little Britain Meat Packers (2012)					inquiries@littlebritainmeatpackers.com	
Lloyd Miedema & Sons	1812 Thompson Road					519-443-4170
Lloyd Miedema & Sons	East, RR 5	Waterford	N0E 1Y0			
Lloyd Miedema & Sons	1142 Reidsville Road, RR					519-632-8634
Louro Bros. Meats Ltd.	1	Ayr	N0B 1E0			
Louro Bros. Meats Ltd.	4510 Hwy 6, RR 3, PO					905-768-0313
Lowbank Farms Ltd.	Box 786	Hagersville	N0A 1H0			
Lowbank Farms Ltd.	282 Escott Rockport Rd,					
Lynch's Slaughterhouse	RR 2	Mallorytown	K0E 1R0			

Plant Name	Address	City	Postal Code	Website	E-mail	Fax
Lynch's Slaughterhouse	34 Holland Road, RR 1	Mallorytown	K0E 1R0			
Lynch's Slaughterhouse	32 Holland Road, RR 1	Lansdowne	K0E 1L0			
Macgregors Meat Seafood Ltd	265 Garyray Dr	Toronto	M9L 1P2	http://www.macgregors.com/ garryl@macgregors.com	angela@macgregors.com john@macgregors.com paul@macgregors.com	888-584-3663
Manilla Halal Meats	18619 Simcoe St, RR 2	Oakwood	K0M 2M0	-		
Manilla Halal Meats	9218 Yonge St	Richmond Hill	L4C 7A2			
Manitoulin Island Community Abattoir Inc.	3120 Monument Road	Providence Bay	P0P 1T0			
Maple Leaf Foods Cappola Cartwright	92 Cartwright Ave	Toronto	M6A 1V2	http://www.mapleleaffoods.com/	* Use the website	416-787-1535
Maple Leaf Foods Cappola Lepage	25 Lepage Ct	Toronto	M3J 3M3		sales@cappolafood.com	
Maple Leaf Foods Inc	100 Ethel Avenue	Toronto	M6N 4Z7			
Maple Leaf Foods Inc	550 Kipling Avenue	Toronto	M8Z 5E9			
Maple Leaf Foods Inc	30 St Clair Ave W, Suite 1500	Toronto	M4V 3A1			
Mastro Foods Holdings Ltd	353 Humberline Drive	Toronto	M9W 5X3			
Matar Kabob House and Meat Shop	3515 Albion Rd S,					
Matar Meat Shop	Gloucester	Ottawa	K1T 1P1	http://matarmeatshopkabobhouse.ca/		
Matar Meat Shop	1077 Cyrville Road	Ottawa	K1J 7S6			
Matar Meat Shop	2527 Bank St	Ottawa	K1V 8R9			
Matar Meats	2690 Stagecoach Rd, RR 1	Osgoode	K0A 2W0			
Mcgarroch of Micksburg Custom Butchering	2749 Micksburg Rd., RR 3	Pembroke	K8A 6W4			613-732-7181
Meat Express	2-328 Passmore Ave	Toronto	M1V 3N8			
Metheral Meats	RR 1, 9093 6/7					705-466-3135
Metheral Meats	Nottawasaga Side Rd.	Glen Huron	L0M 1L0			
Metheral Meats	9093 Township Rd 6 & 7	Glen Huron	L0M 1L0			
Metheral Meats	Dunedin	Creemore	L0M 1G0			
Metheral Meats	34 Caroline St W	Creemore	L0M 1G0			
Metzger Meat Products	180 Brock Avenue, Box 514	Hensall	N0M 1X0	http://www.metzgermeats.com/	info@metzgermeats.com	
Miedema's Country Meats	41130 Thames Road East	Exeter	N0M 1S5			
Miedema's Meat Market Ltd	129 Huron Street	Embro	N0J 1J0			519-475-4790
Miky's Smoke House	30 Hamann Road	Hearst	P0L 1N0	http://www.mikyssmokehouse.ca/	mikys@ntl.sympatico.ca	705-362-8433
Millgrove Packers Limited	549 Conc. 5 W., RR 2	Waterdown	L0R 2H2			905-689-6272
Mogk's Butcher Shop	516702 East Zorra, RR 2	Tavistock	N0B 2R0			
Morrison Custom Poultry Processing Ltd.	3711 Lindsay Highway, RR 3	Omeme	K0L 2W0			
Mount Brydges Abattoir Ltd.	21618 Adelaide Road, RR 1	Mount Brydges	N0L 1W0			519-264-2217
Mr. Beef	223 Mcwatty Road, Po Box 51	Pakenham	K0A 2X0	http://www.mrbeefstore.com/	* Use the website	
N & H Food Co Limited	2-125 Union St	Toronto	M6N 3N4	http://www.nguyenhuong.ca/	* Use the website	
Newmarket Meat Packers Ltd.	3491 Highway 89	Cookstown	L0L 1L0			
Newmarket Meat Packers Ltd.	15452 Warden Ave.	Newmarket	L3Y 9E5	http://goo.gl/I356OI	* Use the website	905-836-9357

Plant Name	Address	City	Postal Code	Website	E-mail	Fax
Niagara Sausage & Meat Products Limited	40 Ridge Road, RR 4 4051 Lakeshore Road, RR 2	Welland	L3B 5N7	http://niagarasausage.com/		905-734-3948
Norfolk Packers Northeast Meat Packers Ltd (Whitmore Meat Packers Ltd)	2 3765 Line 12 North, RR 2	St. Williams	N0E 1P0	http://goo.gl/hZNsu8	* Use the website	519-586-7459
Northern Meat Packers and Abattoir Ltd.	266 Mcfadden Line, PO Box 175	Coldwater	L0K 1E0			705-325-8511
Northern Quality Meats Ltd.	290 Deplonty Road	Trout Creek	P0H 2L0			705-723-5758
Norwich Packers Limited	11 Robson Street	Bruce Mines	P0R 1C0			705-782-0533
Oak Knoll Farms	5754 3rd Line, RR 1	Norwich	N0J 1P0	http://www.norpacbeef.com/	* Use the website	519-468-2050
Ontario Halal Meat Packers	5593 Halton 25	Hillsburgh	N0B 1Z0	http://oakknollfarms.ca/	* Use the website	
Ontario Halal Meat Packers	5593 Highway #25	Milton	L9T 2X5			905-875-0370
Ontario Lamb Company - A Division of Newmarket Meat Packers	15452 Warden Ave, RR 3 1120 - 100 Conestoga	Newmarket	L3Y 4W1	http://www.ontariolamb.ca/	info@ontariolamb.ca	905-836-9357
Ontario Turkey	College Boulevard 2043 Drummond Line, RR 7	Kitchener	N2P 2N6	http://turkeyrecipes.ca/	info@turkeyfarmers.on.ca	519-748-2742
Otonabee Meat Packers Ltd.	2553 River Street West, PO Box 484	Peterborough	K9J 6X8			705-743-0998
Palmateer's Abattoir Ltd.		Tweed	K0K 3K0			613-478-3801
Peel Sausage Inc.	7860 Sixth Line, RR 2 Lot 6, Conc 5, Durham Region	Drayton	N0G 1P0		delmer@peelsausageinc.com	519-638-3444
Pine Ridge Packers (2003) Pine Ridge Packers Inc & Steak Heaven	2910 7A Hwy	Scugog Twp	L0B 1B0			
Pine Ridge Packers (2003)	Lot 6, Conc 5 4311 Mastwood Road, RR 3, Stn Main	Blackstock	L0B 1B0			905-342-1173
Prime Cut Meats		Blackstock	L0B 1B0			905-871-5477
Prime Cut Specialty Meats	310 Garrison Rd	Port Hope	L1A 3V7	http://www.primecutsdeliandmeats.com/		416-504-3756
Quality Meat Packers Limited	1-2 Tecumseth St	Fort Erie	L2A 1M7	http://www.legacypork.com/	mmiller@qualitymeats.on.ca	613-377-1520
Quinn's Brian Meats	3998 Country Road 1 E	Toronto	M5V 2R5	http://www.legacypork.com/		
Rainy River District Regional Abattoir Inc.	Box 299, 26 Byng Street	Yarker	K0K 3N0	http://www.quinnsmeats.com/	* Use the website	
Ralph Bos Meats Ltd.	3742 Egremont Drive	Emo	P0W 1E0			
Ranchland Meats Ltd.	2021 Bruce Road #3, RR 1	Strathroy	N7G 3H6	http://ralphbosmeats.ca/		
Reiche Meat Products Ltd.	38 B Line Rd	Cargill	N0G 1J0			
Reiche Meat Products Ltd.	555 Reiche Rd., RR 3	Pembroke	K8A 6W4			
Reist & Weber Butchering Custom Killing & Whole Sales Pork	RR 1	Pembroke	K8A 6W4			
Rideau Meats Ltd.	12090 Hwy 15 N, RR 6	St. Jacobs	N0B 2N0			
Rua Meats Ltd.	275 Frankford Road, RR 1	Smith Falls	K7A 4S7			
Russell Slaughter House	424 Castor Street	Foxboro	K0K 2B0			613-445-2005

Plant Name	Address	City	Postal Code	Website	E-mail	Fax
Ryding-Regency Meat Packers Ltd (Genesis Meat Packers Inc)	70 Glen Scarlett Rd	Toronto	M6N 1P4	http://www.rydingregency.com/	info@rydingregency.com	416-767-3249
Sanabil Halal Meat Farm	5309 Spring Creek Road	Smithville	L0R 2A0	http://goo.gl/ciLMVy	sanabil@live.com	905-563-5401
Santa Maria Foods ULC	10 Armthorpe Road	Brampton	L6T 5M4	http://www.sharemastros.com/	custsrv@smfulc.com	
Santa Maria Foods ULC	353 Humberline Drive	Toronto	M9W 5X3			
Sara's Natural Pork	4922 LaSalle Line	Petrolia	N0N 1R0	http://fieldfarms.ca/	info@fieldfarms.ca info@fmltd.ca	519-882-3988
Sargent Farms Ltd.	61 Garden Lane	Milton	L9T 2P7	http://www.sargentfarms.ca/		905-878-8998
Schefter Poultry Processing	44783 Harriston Road 193064 Amaranth East,	Gorrie	N0G 1X0			
Sheik Halal Farms Inc.	Luther Townline	Grand Valley	L9W 0M3			
Sheik Halal Farms Inc.	12 Steinway Blvd Unit 18	Toronto	M9W 6M5	http://www.sheikhalal.com/	sheik@sheikhalal.com	
Smokey Joe's	7949 Highway #7	Peterborough	K9J 6X3			
Springwater Packers	9040 Springwater Rd, Rr 5	Aylmer	N5H 2R4			
Sprucedale Quality Meats Inc.	Rr 1, 438 Fourth Avenue	Sprucedale	P0A 1Y0	http://www.sprucedalemeats.com/	* Use the website	705-685-7362
St Ann's Foods Inc.	145 Bethridge Rd	Toronto	M9W 1N4			
St. Helen's Meat Packers Limited (Elbee Meat Packers Limited)	706-208 Bloor St W	Toronto	M5S 3B4			
St. Helen's Meat Packers Limited (Elbee Meat Packers Limited)	1-3 Glen Scarlett Rd	Toronto	M6N 1P5	http://www.sthelensmeat.com/	mail@sthelensmeat.com	416-769-0649
Stayner Meat Packers Ltd.	352 Warrington Road 11544 Northumberland Rd. 29, Rr 4	Stayner	L0M 1S0	http://www.staynermeatpackers.com/	staynermeatpackers@hotmail.ca	
Taylor's Custom Meats		Roseneath	K0K 2X0	http://www.tcm.freewebspace.com/	taylorcustommeats@hotmail.com haybon@eagle.ca	
Tayyibat Meats Farm	8394 Church Hill Road 3099 Broadway Street, PO Box 416	Alliston	L6R 1V1	-		
The Alvinston Butcher		Alvinston	N0N 1A0			
The Beef Way (1997)	261 Dunharm St	Kincardine	N2Z 2X9			519-396-5645
The Burt Farm	1295 Tenth Line	Gore Bay	P0P 1H0	http://goo.gl/J1iK9G	burtfarm@xplonet.com	
The Chicken Coup	1302 Garage Road 500 Exmouth Street, Unit 13	Burk's Falls	P0A1C0			
The Country Butcher/Lambton Meats Thunder Bay Meat Processing Company (1986) Limited	4754 Oliver Road, RR 1	Sarnia	N7T 5P4			807-935-2231
Tilbury Abattoir		Murillo	P0T 2G0			519-682-2644
Tilbury Abattoir and Meats	4049 Bonneau Line, RR 1 17 Superior St 13200 Mackenzie Rd., RR 2	Tilbury	N0P 2L0			
Tom Henderson Custom Meat Cutting Town and Country Abattoir		Tilbury	N0P 2L0			
Town and Country Farms	126 Steeles Ave W	Chesterville	K0C 1H0			613-448-3643
Town and Country Meats and Abattoir	13018 Steeles Avenue	Hornby	L0P 1E0			
Town and Country Meats and Abattoir	19950 Hill Road	Hornby	L0P 1E0			
Town and Country Meats and Abattoir	Hwy 21 S	Ridgetown	N0P 2C0			
Town and Country Meats and Abattoir		Ridgetown	N0P 2C0			
Townsend Butchers Inc.	419 Conc. 14, RR 4	Simcoe	N3Y 4K3	http://goo.gl/Ofyvic	* Use the website	519-426-9313
Uplands Pheasantry	6282 Fleming Rd, RR 1	Camlachie	N0N 1E0	http://uplands-pheasantry.ca/	sales@uplands-pheasantry.ca	519-542-2541

Plant Name	Address	City	Postal Code	Website	E-mail	Fax
V. G. Packers Limited	966 Woollen Mill Rd., RR 5	Simcoe	N3Y 4K4	http://www.vgmeats.ca/	* Use the website	519-426-0063
V. G. Packers Limited	131 Upper Centennial Parkway	Stoney Creek	L8J 0B2	-		519-426-0063
Valley Poultry Packers	3134 Main Street	Valley	P0M 1E0	http://valleypoultry.org/	webmaster@valleypoultry.org	905-640-0389
Valtoudis Meat Packers	600 Concession Rd 9, RR 6	Pickering	L1Y 1A3			
Vanessa Meats & Deli Inc.	1971 Regional Road 4	Vanessa	N0E 1V0	http://www.vanessameatsinc.ca/	john@vanessameatsinc.ca	
Walkerton Meat Market	963 Old Durham Road, RR 2	Walkerton	N0G 2V0			
Wallace Beef Inc.	239 Durham St E	Walkerton	N0G 2V0			
Wallace Beef Inc.	3766 Hwy. 15	Joyceville	K0H 1Y0			613-536-6499
Wallace Beef Inc.	3505 Hwy 35, RR 3	Odessa	K0H 2H0			613-536-6499
Wall's Pork Shop	178 Wall St, PO Box 84	Oxdrift	P0V 2J0			807-937-2457
Wayne's Meat Products Inc.	8794 Indian Line, RR 1	Hagersville	N0A 1H0			
Wayne's Meat Products Inc.	8794 Haldimand Road 20	Hagersville	N0A 1H0			
Wayne White	1697 County Road #22	Belle River	N0R 1A0	http://www.whitesmeat.com/	wayne@whitesmeat.com	
Weiland Meats Ltd.	340 Centre Street	Petrolia	N0N 1R0		weilandmeatsltd@on.aibn.com	519-882-1215
Wellington Poultry Ltd.	7514 Wellington Road 109, RR 4	Arthur	N0G 1A0			519-848-6818
Weston Abattoir Ltd.	5409 North Talbot Road	Maidstone	N0R 1K0	http://goo.gl/ZjX4sm	* Use the website	519-737-1200
Williamson Farms	2387 4Th Conc. West, RR 1	Lambton	N0N 1J3	http://williamsonfarms.ca/		
Williamson Farms Country Store	14 King St. W.	Forest	N0N 1J0	-		
Willie's Meats Ltd.	1	Troy	L0R 2B0			
Windcrest Meat Packers	1350 Scugog - 3rd Line	Port Perry	L9L 1B3	http://goo.gl/PwZvHd	* Use the website	905-985-9393
York Chicken Wholesale Ltd	116 Ryding Ave	Toronto	M6N 1H2	-		
York Chicken Wholesale Ltd	188 New Toronto Street	Toronto	M8V 2E8	http://www.yorkchicken.com/	abarocas@yorkchicken.com	416-855-0091
Yves' Prime Cut Meats	883306 Hwy 65	Liskeard	P0J 1P0	-	ypcm@ntl.sympatico.ca	705-647-9845
Zamani & Sons	6120 Yonge St	Toronto	M2M 3W7	http://www.zamanimeats.com/		905-482-8874
Zehr's Country Market	70963 Bronson Line	Dashwood	N0M 1N0		paulzehr@tcc.on.ca	519-565-2280
Zehr's Country Market	75073 Bluewater Hwy RR 1	Bayfield	N0M 1G0		countrymarket@cyg.net	519-565-2280
Zehr's Country Market	1	Bayfield	N0M 1G0			519-565-2280
Zehr's Country Market	6979 Millbank Main St	Millbank	N0K 1L0			2280

Appendix G. Research ethics board approval and renewal.



To: Ciro Fernando Bustillo Lecompte
 Environmental Applied Science and Management

Re: REB 2013-190: Combination of Biological Processes and Advanced Oxidation Technologies for the Treatment of Actual
 Wastewater from the Meat Processing Sector in Ontario

Date: August 16, 2013

Dear *Ciro Fernando Bustillo Lecompte*,

The review of your protocol REB File REB 2013-190 is now complete. The project has been approved for a one-year period. Please note that before proceeding with your project, compliance with other required University approvals/certifications, institutional requirements, or governmental authorizations may be required.

This approval may be extended after one year upon request. Please be advised that if the project is not renewed, approval will expire and no more research involving humans may take place. If this is a funded project, access to research funds may also be affected.

Please note that REB approval policies require that you adhere strictly to the protocol as last reviewed by the REB and that any modifications must be approved by the Board before they can be implemented. Adverse or unexpected events must be reported to the REB as soon as possible with an indication from the Principal Investigator as to how, in the view of the Principal Investigator, these events affect the continuation of the protocol.

Finally, if research subjects are in the care of a health facility, at a school, or other institution or community organization, it is the responsibility of the Principal Investigator to ensure that the ethical guidelines and approvals of those facilities or institutions are obtained and filed with the REB prior to the initiation of any research.

Please quote your REB file number (REB 2013-190) on future correspondence.

Congratulations and best of luck in conducting your research.

A handwritten signature in black ink, appearing to read "Lynn Lavallée".

Lynn Lavallée, Ph.D.

Chair, Research Ethics Board

To: Ciro Fernando Bustillo Lecompte
 Environmental Applied Science and Management

Re: REB 2013-190: Combination of Biological Processes and Advanced Oxidation Technologies for the Treatment of Actual Wastewater from the Meat Processing Sector in Ontario Date: August 5, 2014

Dear *Ciro Fernando Bustillo Lecompte*,

The review of your protocol REB File REB 2013-190 is now complete. This is a renewal for REB File. The project has been approved for a one-year period. Please note that before proceeding with your project, compliance with other required University approvals/certifications, institutional requirements, or governmental authorizations may be required.

This approval may be extended after one year upon request. Please be advised that if the project is not renewed, approval will expire and no more research involving humans may take place. If this is a funded project, access to research funds may also be affected.

Please note that REB approval policies require that you adhere strictly to the protocol as last reviewed by the REB and that any modifications must be approved by the Board before they can be implemented. Adverse or unexpected events must be reported to the REB as soon as possible with an indication from the Principal Investigator as to how, in the view of the Principal Investigator, these events affect the continuation of the protocol.

Finally, if research subjects are in the care of a health facility, at a school, or other institution or community organization, it is the responsibility of the Principal Investigator to ensure that the ethical guidelines and approvals of those facilities or institutions are obtained and filed with the REB prior to the initiation of any research.

Please quote your REB file number (REB 2013-190) on future correspondence.

Congratulations and best of luck in conducting your research.



Lynn Lavallée, Ph.D.
Chair, Research Ethics Board

Appendix H. Questionnaire and consent agreement.

RYERSON UNIVERSITY

Yeates School of Graduate Studies

Environmental Applied Science and Management Doctoral Program

QUESTIONNAIRE

A Survey of Wastewater Treatment Practice and Experience in the Meat Processing Sector in Ontario

Should you have any questions concerning the completion of the survey, please contact:

Ciro Fernando Bustillo Lecompte
PhD Student, Principal Investigator
Environmental Applied Science and Management
Ryerson University
350 Victoria Street, Toronto, ON M5B 2K3
E-mail: cbustill@ryerson.ca

Dr. Mehrab Mehrvar
Professor
Department of Chemical Engineering
Ryerson University
Phone: 416-979-5000 Ext. 6555
Fax: 416-979-5083
350 Victoria Street, Toronto, ON M5B 2K3
E-mail: mmehrvar@ryerson.ca

Instructions for completing the questionnaire

1. You must agree to the provisions of consent in order to complete the questionnaire.
2. The person(s) with the most knowledge of the plant's present wastewater system should complete this survey.
3. The survey has been prepared in an attempt to make it applicable to various meat processing operations; therefore, not all of the information requested will apply to each facility.
4. The questionnaire is designed for a completion time of up to 30 minutes.
5. If exact data is not available to answer a particular question, please provide your best engineering estimates.
6. To access the questionnaire, you may click [here](#) or on the link below. You may also fill this form along with the consent agreement and return them via e-mail or standard mail to the addresses shown above.
Link: <http://goo.gl/mMiv22>
7. Please complete the questionnaire and return it by e-mail or standard mail to the addresses shown above by Tuesday, December 31, 2013. Please make a copy of this questionnaire for your files, prior its return.

Survey Questions

1. General information

- 1.1. Name of the Plant/Facility: _____
- 1.2. Location Address: _____
- 1.3. Number of years in Operation: _____
- 1.4. Operation days per year: _____

2. Plant operations

Slaughtering

- 2.1. Type of animal slaughtered (please choose all that apply)
- Beef Pork Poultry Other: _____
- 2.2. Average number of animals slaughtered per day: _____
- 2.3. Maximum capacity of slaughtering per day: _____ units
- 2.4. Average live weight per animal slaughtered (please choose one of the following units):
- _____ kg _____ lb _____ other unit: (____)

Cutting, packing, debone, portion control, marination, Instant Quick Frozen, Cooking/Breading, Rendering

2.5. Production of plant operations other than slaughtering (please choose all that apply):

Operation	Production per day	Units	Comments
Cutting		kg	
		lb	
		other: _____	
Packing		kg	
		lb	
		other: _____	
Debone		kg	
		lb	
		other: _____	
Portion control		kg	
		lb	
		other: _____	
Marination		kg	
		lb	
		other: _____	
Instant Quick Frozen		kg	
		lb	
		other: _____	
Cooking/Breading		kg	
		lb	
		other: _____	
Rendering		kg	
		lb	
		other: _____	

3. Water usage

- 3.1. Total plant water usage per day: _____ gallons/d ft³/d m³/d L/d other: _____
- 3.2. Water usage during production shifts (if applicable): 1st: _____. 2nd: _____ m³
- 3.3. Water usage during sanitation shift: _____ gallons/d ft³/d m³/d L/d
- 3.4. Water cost: \$ _____ per: gallons ft³ m³ litre other: _____

4. Wastewater treatment operations

4.1. Wastewater treatment system (please choose all that apply):

- On-site treatment with direct disposal to surface water.
- On-site treatment with direct disposal to land application.
- On-site pre-treatment with indirect disposal to public sewer system.
- No on-site pre-treatment with indirect disposal to public sewer system.
- Other: _____

4.2. Wastewater treatment objectives (please choose all that apply):

- Biological Oxygen Demand (BOD) reduction. Odour control. Mixing. Post aeration
- Nitrogen removal. Phosphorous removal. Solids removal. Fat, oil, and grease removal.
- Chemical Oxygen Demand (COD) reduction. Total Organic Carbon (TOC) reduction. pH.
- Others: _____

4.3. Influent flow:

- Design average: _____ gallons per day ft³/d m³/d L/d other: _____
- Actual average: _____ gallons per day ft³/d m³/d L/d other: _____

5. Wastewater characteristics

Parameter (mg/L, except*)	Influent	Effluent	Permitted level	Sampling frequency
BOD ₅				
COD				
TSS				
NH ₃ -N				
CaCO ₃				
TOC				
TN				
TKN				
TP				
Fat, oil, and grease				
Alkalinity* (mEq/L)				
pH*				

6. Wastewater treatment processes used in the plant/facility (please choose all that apply)

Processes	Additional information
<input type="checkbox"/> Screening	Type: _____ Sizes: _____
<input type="checkbox"/> Equalization basin	Volume: _____
<input type="checkbox"/> Dissolved air flotation (DAF)	Capacity: _____ Volume of solids per day: _____ %Moisture: _____
<input type="checkbox"/> Anaerobic digestion	Type: _____ Volume: _____
<input type="checkbox"/> Activated sludge (i.e. SBR)	Type: _____ Volume: _____
<input type="checkbox"/> Aerated lagoon	Number of ponds: _____ Volume: _____
<input type="checkbox"/> Facultative lagoon	Number of ponds: _____ Volume: _____
<input type="checkbox"/> Storage	Volume: _____ # of disposals/transfers per year: _____
<input type="checkbox"/> Packed tower	Volume: _____
<input type="checkbox"/> Final clarifier	Volume: _____
<input type="checkbox"/> Filtration	Type: _____ Sizes: _____
<input type="checkbox"/> Polishing ponds	Number of ponds: _____ Volume: _____
<input type="checkbox"/> Disinfection	Type: _____ Estimated volume used per year (if applicable): _____
<input type="checkbox"/> Land application	Area: _____ Application rate: _____
<input type="checkbox"/> Public sewer discharge	Volume per day: _____
<input type="checkbox"/> Other aeration systems	Type: _____ Volume: _____
<input type="checkbox"/> Other Anaerobic treatment	Type: _____ Volume: _____
<input type="checkbox"/> Advanced oxidation (i.e. Ozone, UV, H ₂ O ₂)	Type: _____ Estimated volume used per year (if applicable): _____
<input type="checkbox"/> Blood collection	Type: _____ Volume: _____
<input type="checkbox"/> No treatment	Volume of wastewater produced per day: _____
Other: _____	_____
Other: _____	_____
Other: _____	_____
Comments: _____ _____ _____ _____	

7. Samples of the wastewater produced in the facility

Would you like to help with the investigators by providing samples of the slaughterhouse wastewater produced in your facility for research purposes on optimizing treatment methods of this wastewater? (Participation is voluntary. No individual name, plant, or company data will be released)

Yes No

If yes, please complete the contact information in order to follow up:

Contact Name: _____

Job title: _____

E-mail address: _____

Telephone: _____

CONSENT AGREEMENT

A Survey of Wastewater Treatment Practice and Experience in the Meat Processing Sector in Ontario

You are being invited to participate in a research study. Please read this *Consent Agreement* so that you understand what your participation will involve.

Investigators

Ciro Fernando Bustillo Lecompte (*cbustill@ryerson.ca*), Environmental Applied Science and Management Doctoral Program, Ryerson University.*

Supervisor: Dr. Mehrab Mehrvar (*mmehrvar@ryerson.ca*), Department of Chemical Engineering, Ryerson University.

**Results will contribute to doctoral dissertation: "Combination of Biological Processes and Advanced Oxidation Technologies for the Treatment of Actual Wastewater from the Meat Processing Sector in Ontario". This study is sponsored by the Natural Sciences and Engineering Research Council of Canada (NSERC) and Ryerson University. In addition, the results will be published in refereed journals.*

Purpose of the study

The purpose of the study is to determine what are the current wastewater treatment technologies used in the meat processing sector in Ontario; thus, assess possible alternatives in order to minimize the impact of the discharge of these wastewaters to the environment. This survey is conducted in an effort to establish baseline wastewater data.

Description of the study and participation

This study is aiming to collect information on current meat processing plants (MPPs) in Ontario, including characteristics of the actual wastewater, type of animals being processed, number of animals slaughtered per year, and type of treatment/storage/disposal used. The information collected by this survey will be used to determine the range and average production rates, water usage, wastewater generation, treatment, and disposal methods utilized by the poultry processing industry. Financial data collected will be used to characterize the economic impact of water use and wastewater generation on the industry. A copy of the final report will be provided to the companies that participate in the study.

Instructions for completing the questionnaire

8. You must agree to the provisions of consent in order to complete the questionnaire.
9. The person(s) with the most knowledge of the plant's present wastewater system should complete this survey.
10. The survey has been prepared in an attempt to make it applicable to various meat processing operations; therefore, not all of the information requested will apply to each facility.
11. The questionnaire is designed for a completion time of up to 30 minutes.
12. If exact data is not available to answer a particular question, please provide your best engineering estimates.
13. To access the questionnaire, you may click [here](#) or on the link below. You may also fill this form along with the consent agreement and return them via e-mail or standard mail to the addresses shown above.
Link: <http://goo.gl/mMiv22>
14. Please complete the questionnaire and return it by e-mail or standard mail to the addresses shown in the Questions about the study section of this consent agreement by Tuesday, December 31, 2013. Please make a copy of this questionnaire for your files, prior its return.

Risks or discomforts

Potential risks/discomforts are very low. You may choose not to answer a particular question, or discontinue participating, if you wish, for any reason. Taking into account that information obtained through the questionnaire could reveal problems relating to the company's compliance with regulations and may also have an impact upon the relationship of the participants with their employers, no individuals' or company names will be used, this is one way to mitigate the risk.

Benefits of the Study

We hope that this study may be highly beneficial as a contribution to the advancement of knowledge due to the lack of information and enforcement on adequate treatment of Slaughterhouse Wastewaters (SWWs). The investigators cannot guarantee, however, that you will receive any benefits from participating in this study.

Incentives to participate

Participation in this study is voluntary; you will not be paid to participate in this study.

Costs

If you choose to complete and return the survey by standard mail, there will be a potential cost of mailing the questionnaire back.

Confidentiality

The information provided in this questionnaire will be used to develop ranges and averages of wastewater systems at typical types of meat processing operations. Individual plants and company data will be viewed and compiled internally by specified Ryerson University researchers only. Reports, publications, and other information generated as a result of this survey will contain only cumulative data presented by meat processing operation type and treatment in Ontario. No individual plant or company data will be released. Electronic data will be both password-protected and encrypted; hard copy data will be stored securely behind lock-and-key.

Voluntary nature of participation and withdrawal

Participation in this study is voluntary. You can choose whether to be in this study or not. If you volunteer to be in this study, you may withdraw your consent and stop your participation at any time without consequences of any kind. If you choose to withdraw from this study, you may also choose to withdraw your data from the study. At any particular point in the study, you may refuse to answer any particular question or stop participation altogether. You may also choose not to answer any question(s) and still remain in the study. Your choice of whether or not to participate will not influence your future relations with the investigator, departments, or Ryerson University.

Questions about the Study

If you have questions about the research, you may contact:

Ciro Fernando Bustillo Lecompte
PhD Student, Principal Investigator
Environmental Applied Science and Management
Ryerson University
350 Victoria Street, Toronto, ON M5B 2K3
E-mail: cbustill@ryerson.ca

Dr. Mehrab Mehrvar
Professor
Department of Chemical Engineering
Ryerson University
Phone: 416-979-5000 Ext. 6555
Fax: 416-979-5083
350 Victoria Street, Toronto, ON M5B 2K3
E-mail: mmehrvar@ryerson.ca

If you have questions regarding your rights as a human subject and participant in this study, you may contact the Ryerson University Research Ethics Board for information:

Research Ethics Board
c/o Office of the Vice President, Research and Innovation
Ryerson University
350 Victoria Street, Toronto, ON M5B 2K3
Phone: 416-979-5042

Agreement

Your signature below indicates that you have read the information in this agreement and have had a chance to ask any questions you have about the study. Your signature also indicates that you agree to be in the study and have been told that you can change your mind and withdraw your consent to participate at any time. You have been given a copy of this agreement. You have been told that by signing this consent agreement you are not giving up any of your legal rights.

I agree to the provisions of consent

Name of Participant (please print)

Signature of Participant

Date

Appendix I. Respirometer raw data.

AS time (hrs)	oxygen (mg/L)	SWW time (hrs)	oxygen (mg/L)	ABR-AS time (hrs)	oxygen (mg/L)	ABR time (hrs)	oxygen (mg/L)
=====	=====	=====	=====	=====	=====	=====	=====
0.25	0.21	0.25	0.00	0.25	0.00	0.25	0.00
0.50	0.21	0.50	0.21	0.50	0.21	0.50	0.17
0.75	0.66	0.75	0.52	0.75	0.74	0.75	0.49
1.00	0.94	1.00	0.91	1.00	0.96	1.00	0.63
1.25	0.94	1.25	0.91	1.25	0.96	1.25	0.94
1.50	1.16	1.50	1.57	1.50	0.96	1.50	1.50
1.75	1.16	1.75	2.09	1.75	0.97	1.75	1.99
2.00	1.37	2.00	2.58	2.00	0.98	2.00	2.54
2.25	1.89	2.25	4.38	2.25	1.19	2.25	3.10
2.50	2.10	2.50	4.83	2.50	1.79	2.50	4.66
2.75	2.34	2.75	5.53	2.75	2.05	2.75	5.32
3.00	2.56	3.00	6.02	3.00	2.29	3.00	5.95
3.25	2.83	3.25	6.64	3.25	2.52	3.25	6.54
3.50	2.83	3.50	7.41	3.50	2.76	3.50	7.17
3.75	3.03	3.75	7.86	3.75	2.96	3.75	7.69
4.00	3.25	4.00	8.28	4.00	3.15	4.00	8.18
4.25	3.48	4.25	8.91	4.25	3.35	4.25	8.70
4.50	3.70	4.50	9.29	4.50	3.51	4.50	9.12
4.75	3.92	4.75	9.71	4.75	3.68	4.75	9.57
5.00	4.17	5.00	10.20	5.00	3.84	5.00	9.99
5.25	4.17	5.25	10.82	5.25	4.07	5.25	10.58
5.50	4.40	5.50	11.17	5.50	4.23	5.50	11.00
5.75	4.63	5.75	11.56	5.75	4.34	5.75	11.28
6.00	4.63	6.00	11.90	6.00	4.48	6.00	11.66
6.25	5.17	6.25	13.29	6.25	4.65	6.25	12.08
6.50	5.42	6.50	13.67	6.50	5.15	6.50	13.39
6.75	5.42	6.75	13.91	6.75	5.24	6.75	13.63
7.00	5.68	7.00	14.26	7.00	5.39	7.00	14.02
7.25	5.68	7.25	14.61	7.25	5.47	7.25	14.23
7.50	5.87	7.50	14.92	7.50	5.60	7.50	14.57
7.75	5.87	7.75	14.92	7.75	5.67	7.75	14.75
8.00	6.34	8.00	16.31	8.00	5.79	8.00	15.06
8.25	6.52	8.25	16.59	8.25	5.86	8.25	15.24
8.50	6.75	8.50	17.04	8.50	6.05	8.50	15.72
8.75	6.42	8.75	16.35	8.75	6.17	8.75	16.04
9.00	6.92	9.00	17.35	9.00	6.59	9.00	17.14
9.25	6.92	9.25	17.67	9.25	6.67	9.25	17.35
9.50	7.14	9.50	17.67	9.50	6.74	9.50	17.52
9.75	7.14	9.75	17.98	9.75	6.78	9.75	17.63

AS time (hrs)	oxygen (mg/L)	SWW time (hrs)	oxygen (mg/L)	ABR-AS time (hrs)	oxygen (mg/L)	ABR time (hrs)	oxygen (mg/L)
10.00	7.35	10.00	18.22	10.00	6.86	10.00	17.84
10.25	7.69	10.25	19.22	10.25	6.90	10.25	17.94
10.50	7.53	10.50	18.47	10.50	7.02	10.50	18.26
10.75	7.53	10.75	18.82	10.75	7.12	10.75	18.50
11.00	7.69	11.00	19.41	11.00	7.26	11.00	18.88
11.25	8.21	11.25	20.41	11.25	7.69	11.25	19.99
11.50	8.21	11.50	20.69	11.50	7.75	11.50	20.16
11.75	8.37	11.75	20.69	11.75	7.85	11.75	20.41
12.00	8.37	12.00	21.00	12.00	7.90	12.00	20.54
12.25	8.52	12.25	21.17	12.25	7.97	12.25	20.72
12.50	8.72	12.50	21.42	12.50	8.05	12.50	20.93
12.75	8.72	12.75	21.70	12.75	8.14	12.75	21.17
13.00	9.23	13.00	23.01	13.00	8.60	13.00	22.35
13.25	9.23	13.25	23.01	13.25	8.62	13.25	22.42
13.50	9.39	13.50	23.32	13.50	8.70	13.50	22.62
13.75	9.39	13.75	23.60	13.75	8.77	13.75	22.80
14.00	9.53	14.00	23.60	14.00	8.82	14.00	22.94
14.25	9.68	14.25	23.91	14.25	8.90	14.25	23.15
14.50	10.01	14.50	25.23	14.50	8.96	14.50	23.29
14.75	10.22	14.75	25.54	14.75	9.41	14.75	24.46
15.00	10.22	15.00	25.54	15.00	9.47	15.00	24.63
15.25	10.40	15.25	25.96	15.25	9.54	15.25	24.81
15.50	10.55	15.50	25.96	15.50	9.62	15.50	25.02
15.75	10.55	15.75	26.27	15.75	9.66	15.75	25.12
16.00	10.69	16.00	26.48	16.00	9.72	16.00	25.26
16.25	10.80	16.25	26.59	16.25	9.74	16.25	25.33
16.50	10.80	16.50	26.59	16.50	9.79	16.50	25.44
16.75	11.02	16.75	26.83	16.75	9.81	16.75	25.51
17.00	11.02	17.00	26.83	17.00	9.85	17.00	25.61
17.25	11.16	17.25	27.14	17.25	9.99	17.25	25.96
17.50	11.16	17.50	27.42	17.50	10.02	17.50	26.06
17.75	11.43	17.75	27.77	17.75	10.12	17.75	26.31
18.00	11.43	18.00	28.12	18.00	10.17	18.00	26.45
18.25	11.59	18.25	28.33	18.25	9.83	18.25	25.55
18.50	11.26	18.50	27.43	18.50	9.88	18.50	25.69
18.75	11.39	18.75	27.71	18.75	9.91	18.75	25.76
19.00	11.51	19.00	27.96	19.00	9.95	19.00	25.86
19.25	11.67	19.25	28.20	19.25	10.00	19.25	26.00
19.50	11.67	19.50	28.20	19.50	10.05	19.50	26.14
19.75	11.80	19.75	28.48	19.75	10.10	19.75	26.25
20.00	11.99	20.00	28.76	20.00	10.15	20.00	26.39

AS time (hrs)	oxygen (mg/L)	SWW time (hrs)	oxygen (mg/L)	ABR-AS time (hrs)	oxygen (mg/L)	ABR time (hrs)	oxygen (mg/L)
20.25	11.99	20.25	29.21	20.25	10.24	20.25	26.63
20.50	12.15	20.50	29.70	20.50	9.94	20.50	25.84
20.75	11.97	20.75	28.70	20.75	10.02	20.75	26.05
21.00	12.04	21.00	29.15	21.00	10.10	21.00	26.26
21.25	12.19	21.25	29.43	21.25	10.24	21.25	26.61
21.50	12.34	21.50	30.09	21.50	10.31	21.50	26.81
21.75	12.47	21.75	30.54	21.75	10.41	21.75	27.06
22.00	12.80	22.00	30.82	22.00	10.53	22.00	27.37
22.25	12.80	22.25	31.59	22.25	10.65	22.25	27.69
22.50	12.91	22.50	31.94	22.50	10.75	22.50	27.96
22.75	13.12	22.75	32.46	22.75	10.84	22.75	28.17
23.00	13.26	23.00	32.77	23.00	10.94	23.00	28.45
23.25	13.39	23.25	33.50	23.25	11.05	23.25	28.73
23.50	13.84	23.50	33.85	23.50	11.16	23.50	29.01
23.75	13.84	23.75	34.13	23.75	11.28	23.75	29.32
24.00	14.08	24.00	34.55	24.00	11.40	24.00	29.64
24.25	14.23	24.25	35.28	24.25	11.49	24.25	29.88
24.50	14.36	24.50	35.66	24.50	11.64	24.50	30.26
24.75	14.61	24.75	36.33	24.75	11.38	24.75	29.58
25.00	14.76	25.00	36.99	25.00	11.50	25.00	29.89
25.25	14.57	25.25	36.44	25.25	11.66	25.25	30.31
25.50	14.74	25.50	37.10	25.50	11.79	25.50	30.66
25.75	15.06	25.75	37.73	25.75	11.91	25.75	30.97
26.00	15.38	26.00	38.32	26.00	12.02	26.00	31.25
26.25	15.54	26.25	38.70	26.25	12.17	26.25	31.63
26.50	15.69	26.50	39.26	26.50	12.29	26.50	31.94
26.75	15.90	26.75	39.71	26.75	12.41	26.75	32.26
27.00	16.08	27.00	40.38	27.00	12.49	27.00	32.47
27.25	16.34	27.25	40.83	27.25	12.65	27.25	32.88
27.50	16.49	27.50	41.63	27.50	12.78	27.50	33.23
27.75	16.65	27.75	42.01	27.75	12.90	27.75	33.55
28.00	16.94	28.00	42.85	28.00	13.04	28.00	33.89
28.25	17.09	28.25	43.20	28.25	13.21	28.25	34.35
28.50	17.25	28.50	43.93	28.50	13.33	28.50	34.66
28.75	17.59	28.75	44.42	28.75	13.49	28.75	35.08
29.00	17.74	29.00	45.22	29.00	13.74	29.00	35.71
29.25	17.98	29.25	45.98	29.25	13.77	29.25	35.81
29.50	18.13	29.50	46.40	29.50	13.84	29.50	35.98
29.75	18.31	29.75	47.06	29.75	13.96	29.75	36.30
30.00	18.50	30.00	47.48	30.00	14.08	30.00	36.61
30.25	19.04	30.25	49.32	30.25	14.16	30.25	36.82

AS time (hrs)	oxygen (mg/L)	SWW time (hrs)	oxygen (mg/L)	ABR-AS time (hrs)	oxygen (mg/L)	ABR time (hrs)	oxygen (mg/L)
30.50	18.89	30.50	48.67	30.50	13.78	30.50	35.82
30.75	19.42	30.75	50.29	30.75	13.78	30.75	35.82
31.00	19.09	31.00	49.92	31.00	14.16	31.00	36.82
31.25	19.31	31.25	50.27	31.25	14.16	31.25	36.82
31.50	19.85	31.50	52.07	31.50	14.20	31.50	36.93
31.75	20.06	31.75	52.42	31.75	13.83	31.75	35.96
32.00	19.94	32.00	52.11	32.00	14.27	32.00	37.10
32.25	20.09	32.25	52.43	32.25	14.32	32.25	37.24
32.50	20.14	32.50	53.02	32.50	14.40	32.50	37.45
32.75	20.33	32.75	53.33	32.75	14.02	32.75	36.45
33.00	20.51	33.00	53.96	33.00	14.02	33.00	36.45
33.25	20.74	33.25	54.59	33.25	14.06	33.25	36.55
33.50	20.97	33.50	54.83	33.50	14.07	33.50	36.59
33.75	20.97	33.75	55.67	33.75	14.10	33.75	36.66
34.00	21.22	34.00	56.26	34.00	14.21	34.00	36.94
34.25	21.45	34.25	56.57	34.25	14.29	34.25	37.14
34.50	21.45	34.50	56.96	34.50	14.35	34.50	37.32
34.75	21.63	34.75	57.30	34.75	14.41	34.75	37.46
35.00	21.82	35.00	57.93	35.00	14.53	35.00	37.77
35.25	22.02	35.25	58.31	35.25	14.62	35.25	38.01
35.50	22.02	35.50	58.70	35.50	14.91	35.50	38.76
35.75	22.19	35.75	59.15	35.75	14.91	35.75	38.76
36.00	22.38	36.00	59.57	36.00	15.22	36.00	39.56
36.25	22.38	36.25	59.57	36.25	15.22	36.25	39.56
36.50	22.55	36.50	60.23	36.50	15.44	36.50	40.15
36.75	22.75	36.75	60.58	36.75	15.44	36.75	40.15
37.00	22.95	37.00	60.79	37.00	15.71	37.00	40.85
37.25	22.61	37.25	60.41	37.25	15.33	37.25	39.85
37.50	23.15	37.50	61.83	37.50	15.51	37.50	40.33
37.75	23.15	37.75	62.15	37.75	15.51	37.75	40.33
38.00	23.31	38.00	62.46	38.00	15.51	38.00	40.33
38.25	23.48	38.25	62.74	38.25	15.69	38.25	40.79
38.50	23.68	38.50	63.22	38.50	15.84	38.50	41.17
38.75	23.68	38.75	63.92	38.75	15.84	38.75	41.17
39.00	23.86	39.00	64.27	39.00	16.05	39.00	41.73
39.25	24.08	39.25	64.58	39.25	16.14	39.25	41.97
39.50	24.08	39.50	64.90	39.50	16.22	39.50	42.18
39.75	24.27	39.75	65.52	39.75	16.33	39.75	42.46
40.00	24.32	40.00	65.87	40.00	16.36	40.00	42.53
40.25	24.46	40.25	66.19	40.25	16.26	40.25	42.26
40.50	24.64	40.50	66.50	40.50	16.30	40.50	42.37

AS time (hrs)	oxygen (mg/L)	SWW time (hrs)	oxygen (mg/L)	ABR-AS time (hrs)	oxygen (mg/L)	ABR time (hrs)	oxygen (mg/L)
40.75	24.64	40.75	66.85	40.75	16.39	40.75	42.61
41.00	24.82	41.00	67.13	41.00	16.48	41.00	42.85
41.25	25.00	41.25	67.79	41.25	16.64	41.25	43.27
41.50	25.00	41.50	68.21	41.50	16.71	41.50	43.45
41.75	25.16	41.75	68.55	41.75	16.83	41.75	43.76
42.00	25.36	42.00	68.87	42.00	16.95	42.00	44.07
42.25	25.36	42.25	68.22	42.25	17.07	42.25	44.39
42.50	25.57	42.50	69.53	42.50	17.14	42.50	44.56
42.75	25.24	42.75	68.95	42.75	17.25	42.75	44.84
43.00	25.45	43.00	69.68	43.00	17.39	43.00	45.22
43.25	25.65	43.25	70.03	43.25	17.41	43.25	45.26
43.50	25.65	43.50	70.31	43.50	17.53	43.50	45.57
43.75	25.88	43.75	70.72	43.75	17.59	43.75	45.74
44.00	25.88	44.00	71.00	44.00	17.70	44.00	46.02
44.25	26.07	44.25	71.73	44.25	17.80	44.25	46.27
44.50	26.29	44.50	72.19	44.50	17.96	44.50	46.68
44.75	26.29	44.75	72.57	44.75	18.00	44.75	46.79
45.00	26.48	45.00	72.99	45.00	17.69	45.00	46.00
45.25	26.48	45.25	73.37	45.25	17.75	45.25	46.14
45.50	26.69	45.50	73.72	45.50	17.88	45.50	46.49
45.75	26.87	45.75	74.28	45.75	18.28	45.75	47.52
46.00	26.54	46.00	73.59	46.00	18.00	46.00	46.80
46.25	26.75	46.25	73.94	46.25	18.08	46.25	47.01
46.50	26.75	46.50	74.36	46.50	18.17	46.50	47.25
46.75	26.75	46.75	74.81	46.75	18.30	46.75	47.57
47.00	26.95	47.00	75.26	47.00	18.35	47.00	47.70
47.25	26.95	47.25	75.75	47.25	18.39	47.25	47.81
47.50	27.14	47.50	76.38	47.50	18.51	47.50	48.12
47.75	27.14	47.75	76.90	47.75	18.55	47.75	48.23
48.00	27.02	48.00	76.11	48.00	18.64	48.00	48.47
48.25	27.02	48.25	76.91	48.25	18.75	48.25	48.75
48.50	27.23	48.50	77.19	48.50	18.81	48.50	48.89
48.75	27.45	48.75	77.64	48.75	18.84	48.75	48.99
49.00	27.45	49.00	78.06	49.00	18.95	49.00	49.27
49.25	27.68	49.25	78.41	49.25	18.66	49.25	48.52
49.50	27.68	49.50	78.82	49.50	18.73	49.50	48.69
49.75	27.89	49.75	79.24	49.75	18.84	49.75	48.97
50.00	28.12	50.00	79.94	50.00	18.90	50.00	49.14
50.25	28.12	50.25	80.25	50.25	18.96	50.25	49.28
50.50	28.32	50.50	80.64	50.50	19.04	50.50	49.49
50.75	28.51	50.75	81.23	50.75	19.12	50.75	49.70

AS time (hrs)	oxygen (mg/L)	SWW time (hrs)	oxygen (mg/L)	ABR-AS time (hrs)	oxygen (mg/L)	ABR time (hrs)	oxygen (mg/L)
51.00	28.38	51.00	80.54	51.00	19.18	51.00	49.87
51.25	28.61	51.25	80.92	51.25	19.26	51.25	50.08
51.50	28.61	51.50	81.52	51.50	19.34	51.50	50.29
51.75	29.14	51.75	82.90	51.75	19.39	51.75	50.40
52.00	29.05	52.00	82.18	52.00	19.42	52.00	50.50
52.25	29.05	52.25	82.70	52.25	19.53	52.25	50.78
52.50	29.25	52.50	83.12	52.50	19.59	52.50	50.92
52.75	29.44	52.75	83.40	52.75	19.62	52.75	51.02
53.00	29.44	53.00	83.75	53.00	19.72	53.00	51.27
53.25	29.66	53.25	84.23	53.25	19.77	53.25	51.41
53.50	29.88	53.50	84.69	53.50	19.83	53.50	51.55
53.75	29.88	53.75	85.03	53.75	19.86	53.75	51.62
54.00	30.08	54.00	85.59	54.00	19.92	54.00	51.79
54.25	30.08	54.25	85.94	54.25	19.99	54.25	51.96
54.50	30.31	54.50	86.29	54.50	20.06	54.50	52.14
54.75	30.31	54.75	86.78	54.75	20.08	54.75	52.21
55.00	30.49	55.00	86.78	55.00	20.15	55.00	52.38
55.25	30.49	55.25	87.23	55.25	20.23	55.25	52.59
55.50	30.69	55.50	87.61	55.50	20.29	55.50	52.76
55.75	30.69	55.75	88.13	55.75	20.31	55.75	52.80
56.00	30.90	56.00	88.41	56.00	20.34	56.00	52.87
56.25	30.90	56.25	88.80	56.25	20.43	56.25	53.11
56.50	31.11	56.50	89.11	56.50	20.48	56.50	53.25
56.75	30.78	56.75	88.18	56.75	20.52	56.75	53.36
57.00	30.99	57.00	88.53	57.00	20.61	57.00	53.57
57.25	30.99	57.25	89.05	57.25	20.68	57.25	53.77
57.50	31.18	57.50	89.29	57.50	20.76	57.50	53.98
57.75	31.18	57.75	89.68	57.75	20.84	57.75	54.19
58.00	31.40	58.00	90.09	58.00	20.91	58.00	54.37
58.25	31.40	58.25	90.41	58.25	20.97	58.25	54.51
58.50	31.40	58.50	90.72	58.50	21.02	58.50	54.65
58.75	31.61	58.75	91.04	58.75	21.06	58.75	54.75
59.00	31.61	59.00	91.35	59.00	21.06	59.00	54.75
59.25	31.84	59.25	91.63	59.25	21.06	59.25	54.75
59.50	31.84	59.50	92.15	59.50	21.06	59.50	54.75
59.75	31.84	59.75	92.43	59.75	21.06	59.75	54.75
60.00	31.74	60.00	91.71	60.00	21.06	60.00	54.75
60.25	31.74	60.25	92.02	60.25	21.06	60.25	54.75
60.50	31.96	60.50	92.40	60.50	21.06	60.50	54.75
60.75	31.96	60.75	92.61	60.75	21.06	60.75	54.75
61.00	31.96	61.00	92.96	61.00	21.09	61.00	54.82

AS time (hrs)	oxygen (mg/L)	SWW time (hrs)	oxygen (mg/L)	ABR-AS time (hrs)	oxygen (mg/L)	ABR time (hrs)	oxygen (mg/L)
61.25	32.15	61.25	93.20	61.25	21.09	61.25	54.82
61.50	32.15	61.50	93.55	61.50	21.10	61.50	54.86
61.75	32.35	61.75	93.97	61.75	21.15	61.75	54.99
62.00	32.35	62.00	94.25	62.00	21.18	62.00	55.06
62.25	32.54	62.25	94.63	62.25	21.25	62.25	55.24
62.50	32.54	62.50	94.91	62.50	21.31	62.50	55.41
62.75	32.77	62.75	95.16	62.75	21.31	62.75	55.41
63.00	32.77	63.00	95.54	63.00	21.36	63.00	55.52
63.25	32.77	63.25	95.54	63.25	21.47	63.25	55.83
63.50	32.94	63.50	95.85	63.50	21.50	63.50	55.90
63.75	32.94	63.75	96.06	63.75	21.53	63.75	55.97
64.00	32.94	64.00	96.48	64.00	21.66	64.00	56.32
64.25	33.14	64.25	96.48	64.25	21.73	64.25	56.49
64.50	33.14	64.50	96.79	64.50	21.76	64.50	56.57
64.75	33.14	64.75	97.07	64.75	21.79	64.75	56.65
65.00	33.33	65.00	97.49	65.00	21.82	65.00	56.72
65.25	33.33	65.25	97.49	65.25	21.85	65.25	56.80
65.50	33.33	65.50	97.94	65.50	21.88	65.50	56.88
65.75	33.52	65.75	97.94	65.75	21.91	65.75	56.96
66.00	33.52	66.00	98.22	66.00	21.94	66.00	57.03
66.25	33.52	66.25	98.57	66.25	21.96	66.25	57.10
66.50	33.72	66.50	98.57	66.50	21.99	66.50	57.18
66.75	33.72	66.75	98.85	66.75	22.02	66.75	57.25
67.00	33.72	67.00	99.16	67.00	22.05	67.00	57.32
67.25	33.89	67.25	99.40	67.25	22.08	67.25	57.39
67.50	33.89	67.50	99.72	67.50	22.10	67.50	57.46
67.75	34.07	67.75	100.03	67.75	22.13	67.75	57.53
68.00	34.07	68.00	100.35	68.00	22.16	68.00	57.60
68.25	34.07	68.25	100.69	68.25	22.18	68.25	57.67
68.50	34.26	68.50	100.69	68.50	22.21	68.50	57.73
68.75	34.26	68.75	101.01	68.75	22.23	68.75	57.80
69.00	34.46	69.00	101.36	69.00	22.26	69.00	57.86
69.25	34.46	69.25	101.36	69.25	22.28	69.25	57.92
69.50	34.46	69.50	101.36	69.50	22.30	69.50	57.99
69.75	34.46	69.75	101.36	69.75	22.33	69.75	58.05
70.00	34.46	70.00	101.36	70.00	22.35	70.00	58.11
70.25	34.79	70.25	102.36	70.25	22.37	70.25	58.17
70.50	34.46	70.50	101.36	70.50	22.40	70.50	58.23
70.75	34.79	70.75	102.36	70.75	22.42	70.75	58.29
71.00	34.46	71.00	101.36	71.00	22.44	71.00	58.34
71.25	34.46	71.25	101.36	71.25	22.46	71.25	58.40

AS time (hrs)	oxygen (mg/L)	SWW time (hrs)	oxygen (mg/L)	ABR-AS time (hrs)	oxygen (mg/L)	ABR time (hrs)	oxygen (mg/L)
71.50	34.46	71.50	101.36	71.50	22.48	71.50	58.46
71.75	34.46	71.75	101.36	71.75	22.51	71.75	58.51
72.00	34.46	72.00	101.36	72.00	22.53	72.00	58.56
72.25	34.46	72.25	101.36	72.25	22.55	72.25	58.62
72.50	34.46	72.50	101.36	72.50	22.57	72.50	58.67
72.75	34.46	72.75	101.36	72.75	22.59	72.75	58.72
73.00	34.46	73.00	101.36	73.00	22.61	73.00	58.77
73.25	34.46	73.25	101.36	73.25	22.62	73.25	58.82
73.50	34.59	73.50	101.36	73.50	22.64	73.50	58.87
73.75	34.59	73.75	101.63	73.75	22.66	73.75	58.92
74.00	34.76	74.00	101.95	74.00	22.68	74.00	58.96
74.25	34.76	74.25	102.33	74.25	22.70	74.25	59.01
74.50	34.76	74.50	102.33	74.50	22.71	74.50	59.05
74.75	34.91	74.75	102.57	74.75	22.73	74.75	59.10
75.00	34.91	75.00	102.89	75.00	22.75	75.00	59.14
75.25	35.04	75.25	103.20	75.25	22.76	75.25	59.18
75.50	35.04	75.50	103.51	75.50	22.78	75.50	59.22
75.75	35.32	75.75	103.83	75.75	22.80	75.75	59.26
76.00	35.32	76.00	104.32	76.00	22.81	76.00	59.30
76.25	35.52	76.25	104.52	76.25	22.83	76.25	59.34
76.50	35.52	76.50	104.80	76.50	22.84	76.50	59.38
76.75	35.68	76.75	105.15	76.75	22.85	76.75	59.41
77.00	35.68	77.00	105.40	77.00	22.87	77.00	59.45
77.25	35.68	77.25	105.81	77.25	22.88	77.25	59.49
77.50	35.90	77.50	105.81	77.50	22.89	77.50	59.52
77.75	35.90	77.75	106.27	77.75	22.91	77.75	59.55
78.00	36.05	78.00	106.51	78.00	22.92	78.00	59.59
78.25	36.05	78.25	106.89	78.25	22.93	78.25	59.62
78.50	36.25	78.50	107.24	78.50	22.94	78.50	59.65
78.75	36.25	78.75	107.24	78.75	22.95	78.75	59.68
79.00	36.25	79.00	107.83	79.00	22.97	79.00	59.71
79.25	36.46	79.25	108.04	79.25	22.98	79.25	59.73
79.50	36.46	79.50	108.04	79.50	22.99	79.50	59.76
79.75	36.46	79.75	108.39	79.75	23.00	79.75	59.79
80.00	36.67	80.00	108.67	80.00	23.01	80.00	59.81
80.25	36.67	80.25	108.98	80.25	23.02	80.25	59.84
80.50	36.88	80.50	109.33	80.50	23.02	80.50	59.86
80.75	36.88	80.75	109.61	80.75	23.03	80.75	59.88
81.00	36.88	81.00	109.89	81.00	23.04	81.00	59.90
81.25	37.08	81.25	110.20	81.25	23.05	81.25	59.92
81.50	37.08	81.50	110.48	81.50	23.06	81.50	59.94

AS time (hrs)	oxygen (mg/L)	SWW time (hrs)	oxygen (mg/L)	ABR-AS time (hrs)	oxygen (mg/L)	ABR time (hrs)	oxygen (mg/L)
81.75	37.29	81.75	111.21	81.75	23.06	81.75	59.96
82.00	37.29	82.00	111.21	82.00	23.07	82.00	59.98
82.25	37.51	82.25	111.74	82.25	23.08	82.25	60.00
82.50	37.51	82.50	112.26	82.50	23.08	82.50	60.01
82.75	37.42	82.75	111.81	82.75	23.09	82.75	60.03
83.00	37.95	83.00	113.30	83.00	23.10	83.00	60.04
83.25	37.62	83.25	112.96	83.25	23.10	83.25	60.06
83.50	37.82	83.50	113.70	83.50	23.11	83.50	60.07
83.75	38.37	83.75	114.04	83.75	23.11	83.75	60.08
84.00	38.04	84.00	114.67	84.00	23.11	84.00	60.09
84.25	38.26	84.25	115.16	84.25	23.12	84.25	60.10
84.50	38.81	84.50	116.54	84.50	23.12	84.50	60.11
84.75	38.48	84.75	116.24	84.75	23.13	84.75	60.13
85.00	39.05	85.00	117.80	85.00	23.13	85.00	60.14
85.25	38.71	85.25	117.14	85.25	23.14	85.25	60.15
85.50	38.96	85.50	117.49	85.50	23.14	85.50	60.16
85.75	39.29	85.75	119.15	85.75	23.14	85.75	60.17
86.00	39.22	86.00	118.33	86.00	23.15	86.00	60.18
86.25	39.22	86.25	118.61	86.25	23.15	86.25	60.19
86.50	39.43	86.50	118.85	86.50	23.16	86.50	60.20
86.75	39.77	86.75	119.23	86.75	23.16	86.75	60.21
87.00	39.77	87.00	120.23	87.00	23.16	87.00	60.22
87.25	39.77	87.25	120.23	87.25	23.17	87.25	60.23
87.50	39.43	87.50	119.23	87.50	23.17	87.50	60.24
87.75	39.77	87.75	120.23	87.75	23.18	87.75	60.26
88.00	39.77	88.00	120.23	88.00	23.18	88.00	60.27
88.25	39.77	88.25	120.51	88.25	23.19	88.25	60.28
88.50	39.77	88.50	120.51	88.50	23.19	88.50	60.29
88.75	39.77	88.75	120.69	88.75	23.19	88.75	60.30
89.00	39.77	89.00	120.69	89.00	23.20	89.00	60.31
89.25	39.91	89.25	120.97	89.25	23.20	89.25	60.32
89.50	39.91	89.50	120.97	89.50	23.21	89.50	60.33
89.75	39.91	89.75	121.28	89.75	23.21	89.75	60.34
90.00	39.91	90.00	121.28	90.00	23.21	90.00	60.35
90.25	39.91	90.25	121.28	90.25	23.22	90.25	60.36
90.50	39.91	90.50	121.52	90.50	23.22	90.50	60.38
90.75	39.91	90.75	121.52	90.75	23.23	90.75	60.39
91.00	39.91	91.00	121.52	91.00	23.23	91.00	60.40
91.25	39.91	91.25	121.52	91.25	23.24	91.25	60.41
91.50	39.91	91.50	121.52	91.50	23.24	91.50	60.42
91.75	39.91	91.75	121.52	91.75	23.24	91.75	60.43

AS time (hrs)	oxygen (mg/L)	SWW time (hrs)	oxygen (mg/L)	ABR-AS time (hrs)	oxygen (mg/L)	ABR time (hrs)	oxygen (mg/L)
92.00	39.91	92.00	121.52	92.00	23.25	92.00	60.44
92.25	39.91	92.25	121.52	92.25	23.25	92.25	60.45
92.50	39.91	92.50	121.52	92.50	23.26	92.50	60.46
92.75	40.24	92.75	121.52	92.75	23.26	92.75	60.47
93.00	39.91	93.00	121.52	93.00	23.27	93.00	60.48
93.25	39.91	93.25	121.52	93.25	23.27	93.25	60.50
93.50	40.24	93.50	122.52	93.50	23.27	93.50	60.51
93.75	39.91	93.75	121.52	93.75	23.28	93.75	60.52
94.00	40.24	94.00	122.52	94.00	23.28	94.00	60.53
94.25	40.24	94.25	122.52	94.25	23.29	94.25	60.54
94.50	40.24	94.50	122.52	94.50	23.29	94.50	60.55
94.75	40.24	94.75	122.52	94.75	23.29	94.75	60.56
95.00	39.91	95.00	121.52	95.00	23.30	95.00	60.57
95.25	40.24	95.25	122.52	95.25	23.30	95.25	60.58
95.50	40.24	95.50	122.52	95.50	23.31	95.50	60.59
95.75	40.24	95.75	122.52	95.75	23.31	95.75	60.60
96.00	40.24	96.00	122.52	96.00	23.32	96.00	60.62
96.25	40.24	96.25	122.52	96.25	23.32	96.25	60.63
96.50	40.24	96.50	122.52	96.50	23.32	96.50	60.64
96.75	40.24	96.75	122.52	96.75	23.33	96.75	60.65
97.00	40.24	97.00	122.52	97.00	23.33	97.00	60.66
97.25	40.24	97.25	122.52	97.25	23.34	97.25	60.67
97.50	40.24	97.50	122.52	97.50	23.34	97.50	60.68
97.75	40.24	97.75	122.52	97.75	23.34	97.75	60.69
98.00	40.24	98.00	122.52	98.00	23.35	98.00	60.70
98.25	40.24	98.25	122.52	98.25	23.35	98.25	60.71
98.50	40.24	98.50	122.52	98.50	23.36	98.50	60.72
98.75	40.24	98.75	122.52	98.75	23.36	98.75	60.73
99.00	40.24	99.00	122.52	99.00	23.37	99.00	60.75
99.25	40.24	99.25	122.52	99.25	23.37	99.25	60.76
99.50	40.24	99.50	122.52	99.50	23.37	99.50	60.77
99.75	40.24	99.75	122.52	99.75	23.38	99.75	60.78
100.00	40.24	100.00	122.52	100.00	23.38	100.00	60.79
100.25	40.24	100.25	122.52	100.25	23.39	100.25	60.80
100.50	40.24	100.50	122.52	100.50	23.39	100.50	60.81
100.75	40.24	100.75	122.52	100.75	23.39	100.75	60.82
101.00	40.24	101.00	122.52	101.00	23.40	101.00	60.83
101.25	40.24	101.25	122.52	101.25	23.40	101.25	60.84
101.50	40.24	101.50	122.52	101.50	23.41	101.50	60.85
101.75	40.24	101.75	122.52	101.75	23.41	101.75	60.87
102.00	40.24	102.00	122.52	102.00	23.42	102.00	60.88

AS time (hrs)	oxygen (mg/L)	SWW time (hrs)	oxygen (mg/L)	ABR-AS time (hrs)	oxygen (mg/L)	ABR time (hrs)	oxygen (mg/L)
102.25	40.24	102.25	122.52	102.25	23.42	102.25	60.89
102.50	40.24	102.50	122.52	102.50	23.42	102.50	60.90
102.75	40.24	102.75	122.52	102.75	23.43	102.75	60.91
103.00	40.24	103.00	122.52	103.00	23.43	103.00	60.92
103.25	40.24	103.25	122.52	103.25	23.44	103.25	60.93
103.50	40.24	103.50	122.52	103.50	23.44	103.50	60.94
103.75	40.24	103.75	122.52	103.75	23.45	103.75	60.95
104.00	40.24	104.00	122.87	104.00	23.45	104.00	60.96
104.25	40.24	104.25	122.87	104.25	23.45	104.25	60.97
104.50	40.24	104.50	123.12	104.50	23.46	104.50	60.99
104.75	40.57	104.75	124.12	104.75	23.46	104.75	61.00
105.00	40.57	105.00	124.39	105.00	23.47	105.00	61.01
105.25	40.24	105.25	123.74	105.25	23.47	105.25	61.02
105.50	40.24	105.50	124.02	105.50	23.47	105.50	61.03
105.75	40.24	105.75	124.61	105.75	23.48	105.75	61.04
106.00	40.24	106.00	124.96	106.00	23.48	106.00	61.05
106.25	40.24	106.25	125.24	106.25	23.49	106.25	61.06
106.50	40.24	106.50	125.59	106.50	23.49	106.50	61.07
106.75	40.24	106.75	125.83	106.75	23.50	106.75	61.08
107.00	40.24	107.00	126.35	107.00	23.50	107.00	61.09
107.25	40.24	107.25	126.60	107.25	23.50	107.25	61.11
107.50	40.32	107.50	126.88	107.50	23.51	107.50	61.12
107.75	40.32	107.75	127.12	107.75	23.51	107.75	61.13
108.00	40.39	108.00	127.43	108.00	23.52	108.00	61.14
108.25	40.46	108.25	127.68	108.25	23.52	108.25	61.15
108.50	40.60	108.50	128.03	108.50	23.52	108.50	61.16
108.75	40.60	108.75	128.44	108.75	23.53	108.75	61.17
109.00	40.60	109.00	128.44	109.00	23.53	109.00	61.18
109.25	40.74	109.25	128.69	109.25	23.54	109.25	61.19
109.50	40.74	109.50	128.69	109.50	23.54	109.50	61.20
109.75	40.74	109.75	128.90	109.75	23.55	109.75	61.21
110.00	40.74	110.00	129.11	110.00	23.55	110.00	61.22
110.25	40.87	110.25	129.31	110.25	23.55	110.25	61.24
110.50	40.99	110.50	129.63	110.50	23.56	110.50	61.25
110.75	41.55	110.75	131.26	110.75	23.56	110.75	61.26
111.00	41.27	111.00	131.27	111.00	23.57	111.00	61.27
111.25	41.76	111.25	131.96	111.25	23.57	111.25	61.28
111.50	42.09	111.50	133.48	111.50	23.58	111.50	61.29
111.75	42.43	111.75	134.15	111.75	23.58	111.75	61.30
112.00	42.65	112.00	134.70	112.00	23.58	112.00	61.31
112.25	42.65	112.25	135.26	112.25	23.59	112.25	61.32

AS time (hrs)	oxygen (mg/L)	SWW time (hrs)	oxygen (mg/L)	ABR-AS time (hrs)	oxygen (mg/L)	ABR time (hrs)	oxygen (mg/L)
112.50	42.80	112.50	135.50	112.50	23.59	112.50	61.33
112.75	43.02	112.75	136.13	112.75	23.60	112.75	61.34
113.00	43.02	113.00	136.45	113.00	23.60	113.00	61.36
113.25	43.03	113.25	137.18	113.25	23.60	113.25	61.37
113.50	43.36	113.50	137.49	113.50	23.61	113.50	61.38
113.75	43.36	113.75	137.66	113.75	23.61	113.75	61.39
114.00	43.53	114.00	138.12	114.00	23.62	114.00	61.40
114.25	43.53	114.25	138.50	114.25	23.62	114.25	61.41
114.50	43.70	114.50	138.88	114.50	23.63	114.50	61.42
114.75	43.70	114.75	139.13	114.75	23.63	114.75	61.43
115.00	43.83	115.00	139.34	115.00	23.63	115.00	61.44
115.25	44.17	115.25	140.79	115.25	23.64	115.25	61.45
115.50	44.01	115.50	140.10	115.50	23.64	115.50	61.46
115.75	44.34	115.75	141.38	115.75	23.65	115.75	61.48
116.00	44.11	116.00	140.38	116.00	23.65	116.00	61.49
116.25	44.57	116.25	141.76	116.25	23.65	116.25	61.50
116.50	44.57	116.50	142.22	116.50	23.66	116.50	61.51
116.75	44.69	116.75	142.36	116.75	23.66	116.75	61.52
117.00	44.69	117.00	142.67	117.00	23.67	117.00	61.53
117.25	44.86	117.25	142.88	117.25	23.67	117.25	61.54
117.50	45.03	117.50	143.51	117.50	23.68	117.50	61.55
117.75	45.18	117.75	143.89	117.75	23.68	117.75	61.56
118.00	45.29	118.00	144.69	118.00	23.68	118.00	61.57
118.25	45.45	118.25	145.18	118.25	23.69	118.25	61.58
118.50	45.54	118.50	145.53	118.50	23.69	118.50	61.60
118.75	45.69	118.75	145.84	118.75	23.70	118.75	61.61
119.00	45.84	119.00	146.68	119.00	23.70	119.00	61.62
119.25	46.06	119.25	147.13	119.25	23.70	119.25	61.63
119.50	46.14	119.50	147.48	119.50	23.71	119.50	61.64
119.75	46.30	119.75	147.72	119.75	23.71	119.75	61.65
120.00	46.30	120.00	147.96	120.00	23.72	120.00	61.66
120.25	46.57	120.25	148.59	120.25		120.25	61.67
120.50	46.57	120.50	149.11	120.50		120.50	61.68
120.75	46.73	120.75	149.74	120.75		120.75	61.69
121.00	46.88	121.00	149.92	121.00		121.00	61.70
121.25	46.98	121.25	150.26	121.25		121.25	61.71
121.50	47.13	121.50	150.96	121.50		121.50	61.73
121.75	47.30	121.75	151.34	121.75		121.75	61.74
122.00	47.43	122.00	152.11	122.00		122.00	61.75
122.25	47.58	122.25	152.39	122.25		122.25	61.76
122.50	47.87	122.50	153.08	122.50		122.50	61.77

AS time (hrs)	oxygen (mg/L)	SWW time (hrs)	oxygen (mg/L)	ABR-AS time (hrs)	oxygen (mg/L)	ABR time (hrs)	oxygen (mg/L)
122.75	47.87	122.75	153.47	122.75		122.75	61.78
123.00	48.05	123.00	153.85	123.00		123.00	61.79
123.25	48.17	123.25	154.09	123.25		123.25	61.80
123.50	48.38	123.50	154.90	123.50		123.50	61.81
123.75	48.56	123.75	155.35	123.75		123.75	61.82
124.00	48.72	124.00	155.80	124.00		124.00	61.83
124.25	48.81	124.25	156.08	124.25		124.25	61.85
124.50	49.03	124.50	156.46	124.50		124.50	61.86
124.75	49.03	124.75	156.99	124.75		124.75	61.87
125.00	49.22	125.00	157.23	125.00		125.00	61.88
125.25	49.22	125.25	157.47	125.25		125.25	61.89
125.50	49.39	125.50	157.93	125.50		125.50	61.90
125.75	49.39	125.75	158.38	125.75		125.75	61.91
126.00	49.56	126.00	158.73	126.00		126.00	61.92
126.25	49.56	126.25	158.97	126.25		126.25	61.93
126.50	49.71	126.50	159.28	126.50		126.50	61.94
126.75	50.21	126.75	160.49	126.75		126.75	61.95
127.00	49.88	127.00	159.77	127.00		127.00	61.97
127.25	50.04	127.25	159.77	127.25		127.25	61.98
127.50	50.04	127.50	160.26	127.50		127.50	61.99
127.75	50.21	127.75	160.68	127.75		127.75	62.00
128.00	50.21	128.00	160.99	128.00		128.00	62.01
128.25	50.31	128.25	161.27	128.25		128.25	62.02
128.50	50.50	128.50	161.44	128.50		128.50	62.03
128.75	50.50	128.75	161.58	128.75		128.75	62.04
129.00	50.50	129.00	161.76	129.00		129.00	62.05
129.25	50.93	129.25	163.00	129.25		129.25	62.06
129.50	51.08	129.50	163.35	129.50		129.50	62.07
129.75	51.08	129.75	163.77	129.75		129.75	62.09
130.00	51.27	130.00	163.77	130.00		130.00	62.10
130.25	51.27	130.25	164.05	130.25		130.25	62.11
130.50	51.27	130.50	164.33	130.50		130.50	62.12
130.75	51.39	130.75	164.67	130.75		130.75	62.13
131.00	51.72	131.00	166.06	131.00		131.00	62.14
131.25	51.87	131.25	166.06	131.25		131.25	62.15
131.50	52.06	131.50	166.30	131.50		131.50	62.16
131.75	52.06	131.75	166.65	131.75		131.75	62.17
132.00	52.06	132.00	166.65	132.00		132.00	62.18
132.25	52.55	132.25	167.93	132.25		132.25	62.19
132.50	52.22	132.50	166.93	132.50		132.50	62.20
132.75	52.22	132.75	167.31	132.75		132.75	62.22

AS time (hrs)	oxygen (mg/L)	SWW time (hrs)	oxygen (mg/L)	ABR-AS time (hrs)	oxygen (mg/L)	ABR time (hrs)	oxygen (mg/L)
133.00	51.89	133.00	166.31	133.00		133.00	62.23
133.25	52.02	133.25	166.66	133.25		133.25	62.24
133.50	52.02	133.50	166.66	133.50		133.50	62.25
133.75	52.02	133.75	166.66	133.75		133.75	62.26
134.00	52.15	134.00	166.97	134.00		134.00	62.27
134.25	52.15	134.25	166.97	134.25		134.25	62.28
134.50	52.15	134.50	167.15	134.50		134.50	62.29
134.75	51.98	134.75	166.39	134.75		134.75	62.30
135.00	51.98	135.00	166.39	135.00		135.00	62.31
135.25	52.31	135.25	167.67	135.25		135.25	62.32
135.50	52.79	135.50	169.05	135.50		135.50	62.34
135.75	52.79	135.75	169.47	135.75		135.75	62.35
136.00	52.64	136.00	168.78	136.00		136.00	62.36
136.25	52.64	136.25	168.78	136.25		136.25	62.37
136.50	52.64	136.50	169.03	136.50		136.50	62.38
136.75	52.77	136.75	169.03	136.75		136.75	62.39
137.00	52.77	137.00	169.27	137.00		137.00	62.40
137.25	52.90	137.25	169.58	137.25		137.25	62.41
137.50	53.05	137.50	170.01	137.50		137.50	62.42
137.75	53.05	137.75	170.08	137.75		137.75	62.43
138.00	53.05	138.00	171.22	138.00		138.00	62.44
138.25	53.15	138.25	170.63	138.25		138.25	62.46
138.50	53.15	138.50	170.63	138.50		138.50	62.47
138.75	53.31	138.75	170.88	138.75		138.75	62.48
139.00	53.31	139.00	171.16	139.00		139.00	62.49
139.25	53.42	139.25	171.40	139.25		139.25	62.50
139.50	53.42	139.50	171.40	139.50		139.50	62.51
139.75	53.42	139.75	171.40	139.75		139.75	62.52
140.00	53.55	140.00	171.71	140.00		140.00	62.53
140.25	53.55	140.25	171.71	140.25		140.25	62.54
140.50	53.55	140.50	171.71	140.50		140.50	62.55
140.75	53.55	140.75	172.10	140.75		140.75	62.56
141.00	53.65	141.00	172.10	141.00		141.00	62.58
141.25	53.65	141.25	172.48	141.25		141.25	62.59
141.50	53.77	141.50	172.48	141.50		141.50	62.60
141.75	53.77	141.75	172.48	141.75		141.75	62.61
142.00	53.77	142.00	172.72	142.00		142.00	62.62
142.25	53.85	142.25	172.72	142.25		142.25	62.63
142.50	53.85	142.50	173.00	142.50		142.50	62.64
142.75	53.85	142.75	173.00	142.75		142.75	62.65
143.00	54.29	143.00	174.32	143.00		143.00	62.66

AS time (hrs)	oxygen (mg/L)	SWW time (hrs)	oxygen (mg/L)	ABR-AS time (hrs)	oxygen (mg/L)	ABR time (hrs)	oxygen (mg/L)
143.25	53.95	143.25	173.32	143.25		143.25	62.67
143.50	54.04	143.50	173.32	143.50		143.50	62.68
143.75	54.04	143.75	173.59	143.75		143.75	62.69
144.00	54.16	144.00	173.87	144.00		144.00	62.71
144.25	54.16	144.25	173.87	144.25		144.25	
144.50	54.27	144.50	174.19	144.50		144.50	
144.75	54.27	144.75	174.57	144.75		144.75	
145.00	54.27	145.00	174.57	145.00		145.00	
145.25	54.37	145.25	174.85	145.25		145.25	
145.50	54.54	145.50	174.85	145.50		145.50	
145.75	54.54	145.75	175.13	145.75		145.75	
146.00	54.54	146.00	175.13	146.00		146.00	
146.25	54.37	146.25	174.75	146.25		146.25	
146.50	54.56	146.50	175.00	146.50		146.50	
146.75	54.89	146.75	176.00	146.75		146.75	
147.00	54.89	147.00	176.00	147.00		147.00	
147.25	54.89	147.25	176.00	147.25		147.25	
147.50	54.89	147.50	176.28	147.50		147.50	
147.75	55.23	147.75	177.28	147.75		147.75	
148.00	55.23	148.00	177.28	148.00		148.00	
148.25	55.23	148.25	177.28	148.25		148.25	
148.50	55.23	148.50	177.28	148.50		148.50	
148.75	55.30	148.75	177.62	148.75		148.75	
149.00	55.30	149.00	177.62	149.00		149.00	
149.25	55.36	149.25	178.04	149.25		149.25	
149.50	55.36	149.50	178.04	149.50		149.50	
149.75	55.36	149.75	178.04	149.75		149.75	
150.00	55.36	150.00	178.04	150.00		150.00	
150.25	55.41	150.25	178.04	150.25		150.25	
150.50	55.41	150.50	178.29	150.50		150.50	
150.75	55.47	150.75	178.29	150.75		150.75	
151.00	55.52	151.00	178.53	151.00		151.00	
151.25	55.52	151.25	178.53	151.25		151.25	
151.50	55.60	151.50	178.70	151.50		151.50	
151.75	55.60	151.75	178.70	151.75		151.75	
152.00	55.68	152.00	179.09	152.00		152.00	
152.25	55.75	152.25	179.09	152.25		152.25	
152.50	55.75	152.50	179.40	152.50		152.50	
152.75	55.75	152.75	179.40	152.75		152.75	
153.00	55.82	153.00	179.64	153.00		153.00	
153.25	55.89	153.25	179.64	153.25		153.25	

AS time (hrs)	oxygen (mg/L)	SWW time (hrs)	oxygen (mg/L)	ABR-AS time (hrs)	oxygen (mg/L)	ABR time (hrs)	oxygen (mg/L)
153.50	55.96	153.50	179.89	153.50		153.50	
153.75	55.96	153.75	179.89	153.75		153.75	
154.00	56.05	154.00	180.20	154.00		154.00	
154.25	56.05	154.25	180.20	154.25		154.25	
154.50	56.13	154.50	180.41	154.50		154.50	
154.75	56.13	154.75	180.69	154.75		154.75	
155.00	56.21	155.00	181.00	155.00		155.00	
155.25	56.21	155.25	181.00	155.25		155.25	
155.50	56.38	155.50	181.28	155.50		155.50	
155.75	56.38	155.75	181.28	155.75		155.75	
156.00	56.38	156.00	181.63	156.00		156.00	
156.25	56.44	156.25	181.63	156.25		156.25	
156.50	56.55	156.50	181.84	156.50		156.50	
156.75	56.55	156.75	181.84	156.75		156.75	
157.00	56.55	157.00	182.05	157.00		157.00	
157.25	56.64	157.25	182.05	157.25		157.25	
157.50	56.64	157.50	182.29	157.50		157.50	
157.75	56.64	157.75	182.29	157.75		157.75	
158.00	56.64	158.00	182.57	158.00		158.00	
158.25	56.64	158.25	182.57	158.25		158.25	
158.50	56.64	158.50	182.57	158.50		158.50	
158.75	56.71	158.75	182.57	158.75		158.75	
159.00	56.71	159.00	182.57	159.00		159.00	
159.25	56.71	159.25	182.57	159.25		159.25	
159.50	56.71	159.50	182.74	159.50		159.50	
159.75	56.71	159.75	182.74	159.75		159.75	
160.00	56.71	160.00	182.74	160.00		160.00	
160.25	56.71	160.25	182.74	160.25		160.25	
160.50	56.71	160.50	182.74	160.50		160.50	
160.75	56.71	160.75	182.74	160.75		160.75	
161.00	57.05	161.00	183.92	161.00		161.00	
161.25	56.78	161.25	183.23	161.25		161.25	
161.50	57.11	161.50	184.23	161.50		161.50	
161.75	57.11	161.75	184.23	161.75		161.75	
162.00	57.11	162.00	184.23	162.00		162.00	
162.25	57.17	162.25	184.55	162.25		162.25	
162.50	57.17	162.50	184.55	162.50		162.50	
162.75	56.91	162.75	183.79	162.75		162.75	
163.00	57.00	163.00	184.07	163.00		163.00	
163.25	57.34	163.25	184.07	163.25		163.25	
163.50	57.41	163.50	185.42	163.50		163.50	

AS time (hrs)	oxygen (mg/L)	SWW time (hrs)	oxygen (mg/L)	ABR-AS time (hrs)	oxygen (mg/L)	ABR time (hrs)	oxygen (mg/L)
163.75	57.41	163.75	185.42	163.75		163.75	
164.00	57.41	164.00	185.42	164.00		164.00	
164.25	57.50	164.25	185.42	164.25		164.25	
164.50	57.50	164.50	185.70	164.50		164.50	
164.75	57.50	164.75	185.70	164.75		164.75	
165.00	57.58	165.00	186.01	165.00		165.00	
165.25	57.58	165.25	186.01	165.25		165.25	
165.50	57.72	165.50	186.25	165.50		165.50	
165.75	57.87	165.75	186.60	165.75		165.75	
166.00	57.87	166.00	186.60	166.00		166.00	
166.25	57.87	166.25	186.60	166.25		166.25	
166.50	57.87	166.50	186.88	166.50		166.50	
166.75	57.97	166.75	187.30	166.75		166.75	
167.00	57.97	167.00	187.30	167.00		167.00	
167.25	58.02	167.25	187.30	167.25		167.25	
167.50	58.12	167.50	187.75	167.50		167.50	
167.75	58.12	167.75	187.75	167.75		167.75	
168.00	58.12	168.00	187.75	168.00		168.00	
168.25	58.12	168.25	187.75	168.25		168.25	
168.50	58.12	168.50	187.75	168.50		168.50	
168.75	58.12	168.75	188.03	168.75		168.75	
169.00	58.18	169.00	188.03	169.00		169.00	
169.25	58.29	169.25	188.27	169.25		169.25	
169.50	58.62	169.50	189.62	169.50		169.50	
169.75	58.73	169.75	189.97	169.75		169.75	
170.00	58.83	170.00	189.97	170.00		170.00	
170.25	58.50	170.25	189.21	170.25		170.25	
170.50	58.61	170.50	189.42	170.50		170.50	
170.75	58.61	170.75	189.70	170.75		170.75	
171.00	58.73	171.00	190.05	171.00		171.00	
171.25	58.73	171.25	190.12	171.25		171.25	
171.50	58.87	171.50	190.33	171.50		171.50	
171.75	58.96	171.75	190.68	171.75		171.75	
172.00	58.98	172.00	190.68	172.00		172.00	
172.25	59.11	172.25	190.95	172.25		172.25	
172.50	59.11	172.50	190.95	172.50		172.50	
172.75	59.25	172.75	191.27	172.75		172.75	
173.00	59.25	173.00	191.27	173.00		173.00	
173.25	59.25	173.25	191.27	173.25		173.25	
173.50	59.25	173.50	191.62	173.50		173.50	
173.75	59.25	173.75	191.62	173.75		173.75	

AS time (hrs)	oxygen (mg/L)	SWW time (hrs)	oxygen (mg/L)	ABR-AS time (hrs)	oxygen (mg/L)	ABR time (hrs)	oxygen (mg/L)
174.00	59.36	174.00	191.62	174.00		174.00	
174.25	59.36	174.25	191.62	174.25		174.25	
174.50	59.51	174.50	191.89	174.50		174.50	
174.75	59.51	174.75	192.28	174.75		174.75	
175.00	59.51	175.00	192.28	175.00		175.00	
175.25	59.70	175.25	192.28	175.25		175.25	
175.50	59.70	175.50	192.56	175.50		175.50	
175.75	59.70	175.75	192.56	175.75		175.75	
176.00	59.70	176.00	192.56	176.00		176.00	
176.25	59.70	176.25	192.84	176.25		176.25	
176.50	59.70	176.50	192.84	176.50		176.50	
176.75	59.70	176.75	193.22	176.75		176.75	
177.00	59.70	177.00	193.22	177.00		177.00	
177.25	59.70	177.25	193.53	177.25		177.25	
177.50	59.76	177.50	193.53	177.50		177.50	
177.75	59.76	177.75	193.74	177.75		177.75	
178.00	59.84	178.00	194.02	178.00		178.00	
178.25	59.84	178.25	194.33	178.25		178.25	
178.50	59.92	178.50	194.68	178.50		178.50	
178.75	60.04	178.75	194.68	178.75		178.75	
179.00	60.04	179.00	195.03	179.00		179.00	
179.25	60.04	179.25	195.03	179.25		179.25	
179.50	60.12	179.50	195.31	179.50		179.50	
179.75	60.27	179.75	195.55	179.75		179.75	
180.00	60.61	180.00	196.55	180.00		180.00	
180.25	60.27	180.25	195.83	180.25		180.25	
180.50	60.27	180.50	196.00	180.50		180.50	
180.75	60.37	180.75	196.35	180.75		180.75	
181.00	60.37	181.00	196.35	181.00		181.00	
181.25	60.45	181.25	196.35	181.25		181.25	
181.50	60.45	181.50	196.81	181.50		181.50	
181.75	60.61	181.75	196.81	181.75		181.75	
182.00	60.61	182.00	196.81	182.00		182.00	
182.25	60.61	182.25	197.15	182.25		182.25	
182.50	60.61	182.50	197.15	182.50		182.50	
182.75	60.61	182.75	197.15	182.75		182.75	
183.00	60.61	183.00	197.40	183.00		183.00	
183.25	60.61	183.25	197.40	183.25		183.25	
183.50	60.61	183.50	197.40	183.50		183.50	
183.75	60.61	183.75	197.40	183.75		183.75	
184.00	60.61	184.00	197.40	184.00		184.00	

AS time (hrs)	oxygen (mg/L)	SWW time (hrs)	oxygen (mg/L)	ABR-AS time (hrs)	oxygen (mg/L)	ABR time (hrs)	oxygen (mg/L)
184.25	60.61	184.25	197.40	184.25		184.25	
184.50	60.61	184.50	197.68	184.50		184.50	
184.75	60.61	184.75	197.68	184.75		184.75	
185.00	60.70	185.00	197.68	185.00		185.00	
185.25	60.70	185.25	197.68	185.25		185.25	
185.50	60.70	185.50	197.68	185.50		185.50	
185.75	60.70	185.75	197.68	185.75		185.75	
186.00	61.04	186.00	198.68	186.00		186.00	
186.25	61.04	186.25	198.68	186.25		186.25	
186.50	61.04	186.50	198.68	186.50		186.50	
186.75	61.04	186.75	199.03	186.75		186.75	
187.00	61.04	187.00	199.03	187.00		187.00	
187.25	61.04	187.25	199.03	187.25		187.25	
187.50	61.04	187.50	199.03	187.50		187.50	
187.75	61.37	187.75	200.03	187.75		187.75	
188.00	61.04	188.00	199.03	188.00		188.00	
188.25	61.37	188.25	200.03	188.25		188.25	
188.50	61.37	188.50	200.03	188.50		188.50	
188.75	61.37	188.75	200.03	188.75		188.75	
189.00	61.37	189.00	200.03	189.00		189.00	
189.25	61.37	189.25	200.03	189.25		189.25	
189.50	61.37	189.50	200.03	189.50		189.50	
189.75	61.43	189.75	200.27	189.75		189.75	
190.00	61.43	190.00	200.27	190.00		190.00	
190.25	61.43	190.25	200.27	190.25		190.25	
190.50	61.43	190.50	200.27	190.50		190.50	
190.75	61.43	190.75	200.27	190.75		190.75	
191.00	61.52	191.00	200.27	191.00		191.00	
191.25	61.52	191.25	200.27	191.25		191.25	
191.50	61.52	191.50	200.27	191.50		191.50	
191.75	61.52	191.75	200.27	191.75		191.75	
192.00	61.71	192.00	200.27	192.00		192.00	
192.25	61.71	192.25	200.27	192.25		192.25	
192.50	61.71	192.50	200.27	192.50		192.50	
192.75	61.71	192.75	200.27	192.75		192.75	
193.00	61.71	193.00	200.41	193.00		193.00	
193.25	61.71	193.25	200.41	193.25		193.25	
193.50	61.71	193.50	200.41	193.50		193.50	
193.75	61.71	193.75	200.72	193.75		193.75	
194.00	61.71	194.00	200.72	194.00		194.00	
194.25	61.47	194.25	200.21	194.25		194.25	

AS time (hrs)	oxygen (mg/L)	SWW time (hrs)	oxygen (mg/L)	ABR-AS time (hrs)	oxygen (mg/L)	ABR time (hrs)	oxygen (mg/L)
194.50	61.94	194.50	201.21	194.50		194.50	
194.75	61.94	194.75	201.59	194.75		194.75	
195.00	62.07	195.00	201.59	195.00		195.00	
195.25	62.07	195.25	201.59	195.25		195.25	
195.50	62.07	195.50	202.01	195.50		195.50	
195.75	62.16	195.75	202.01	195.75		195.75	
196.00	62.16	196.00	202.29	196.00		196.00	
196.25	62.37	196.25	202.29	196.25		196.25	
196.50	62.37	196.50	202.67	196.50		196.50	
196.75	62.03	196.75	201.67	196.75		196.75	
197.00	62.03	197.00	201.67	197.00		197.00	
197.25	62.37	197.25	202.02	197.25		197.25	
197.50	62.37	197.50	203.02	197.50		197.50	
197.75	62.37	197.75	203.02	197.75		197.75	
198.00	62.12	198.00	202.33	198.00		198.00	
198.25	62.45	198.25	203.33	198.25		198.25	
198.50	62.45	198.50	203.65	198.50		198.50	
198.75	62.54	198.75	203.65	198.75		198.75	
199.00	62.54	199.00	203.65	199.00		199.00	
199.25	62.54	199.25	203.96	199.25		199.25	
199.50	62.66	199.50	204.03	199.50		199.50	
199.75	62.66	199.75	204.03	199.75		199.75	
200.00	62.66	200.00	204.34	200.00		200.00	
200.25	62.79	200.25	204.34	200.25		200.25	
200.50	62.79	200.50	204.34	200.50		200.50	
200.75	62.79	200.75	204.34	200.75		200.75	
201.00	62.79	201.00	204.76	201.00		201.00	
201.25	62.79	201.25	204.76	201.25		201.25	
201.50	62.92	201.50	204.76	201.50		201.50	
201.75	62.92	201.75	204.76	201.75		201.75	
202.00	62.92	202.00	205.11	202.00		202.00	
202.25	62.92	202.25	205.11	202.25		202.25	
202.50	62.92	202.50	205.11	202.50		202.50	
202.75	62.92	202.75	205.39	202.75		202.75	
203.00	62.92	203.00	205.39	203.00		203.00	
203.25	63.01	203.25	205.39	203.25		203.25	
203.50	63.01	203.50	205.39	203.50		203.50	
203.75	63.01	203.75	205.74	203.75		203.75	
204.00	63.10	204.00	205.74	204.00		204.00	

Appendix J. Photoreactor experimental design raw data of the effect of TOC_{in}.

HRT	1 h	
Parameter	Value	Unit
Reactor Volume	1.5	L
TOC _{in}	10	mg/L
H ₂ O ₂	900	mg/L
pH	7	
Recycle ratio	0	
Flow rate	24	ccm
	1.44	L/h
	36	%
HRT	1.04	h
TOC _{eff}	1.8052	mg/L
TOC _{rem}	81.95	%
H ₂ O ₂ _{eff}	20.257	mg/L
	3	L
H ₂ O ₂ _{res}	2.2508	%

HRT	1 h	
Parameter	Value	Unit
Reactor Volume	1.5	L
TOC _{in}	30	mg/L
H ₂ O ₂	900	mg/L
pH	7	
Recycle ratio	0	
Flow rate	24	ccm
	1.44	L/h
	36	%
HRT	1.04	h
TOC _{eff}	8.5594	mg/L
TOC _{rem}	71.47	%
H ₂ O ₂ _{eff}	16.919	mg/L
	4	L
H ₂ O ₂ _{res}	1.8799	%

HRT	1 h	
Parameter	Value	Unit
Reactor Volume	1.5	L
TOC _{in}	50	mg/L
H ₂ O ₂	900	mg/L
pH	7	
Recycle ratio	0	
Flow rate	24	ccm
	1.44	L/h
	36	%
HRT	1.04	h
TOC _{eff}	16.977	mg/L
	1	L
TOC _{rem}	66.05	%
H ₂ O ₂ _{eff}	17.843	mg/L
	3	L
H ₂ O ₂ _{res}	1.9826	%

HRT	1 h	
Parameter	Value	Unit
Reactor Volume	1.5	L
TOC _{in}	70	mg/L
H ₂ O ₂	900	mg/L
pH	7	
Recycle ratio	0	
Flow rate	24	ccm
	1.44	L/h
	36	%
HRT	1.04	h
TOC _{eff}	25.0202	mg/L
TOC _{rem}	64.26	%
H ₂ O ₂ _{eff}	21.1490	mg/L
H ₂ O ₂ _{res}	2.3499	%

HRT	1 h	
Parameter	Value	Unit
Reactor Volume	1.5	L
TOC _{in}	90	mg/L
H ₂ O ₂	900	mg/L
pH	7	
Recycle ratio	0	
Flow rate	24	ccm
	1.44	L/h
	36	%
HRT	1.04	h
TOC _{eff}	32.8541	mg/L
TOC _{rem}	63.50	%
H ₂ O ₂ _{eff}	25.7839	mg/L
H ₂ O ₂ _{res}	2.8649	%

Appendix K. Photoreactor experimental design raw data of the effect of H₂O₂ in.

HRT	1 h	
Parameter	Value	Unit
Reactor Volume	1.5	L
TOC _{in}	50	mg/L
H ₂ O ₂	300	mg/L
pH	7	
Recycle ratio	0	0
Flow rate	24	ccm
	1.44	L/h
	36	%
HRT	1.04	h
TOC _{eff}	19.514	mg/L
TOC _{rem}	60.97	%
H ₂ O ₂ _{eff}	4.6800	mg/L
H ₂ O ₂ _{res}	1.5600	%

HRT	1 h	
Parameter	Value	Unit
Reactor Volume	1.5	L
TOC _{in}	50	mg/L
H ₂ O ₂	600	mg/L
pH	7	
Recycle ratio	0	0
Flow rate	24	ccm
	1.44	L/h
	36	%
HRT	1.04	h
TOC _{eff}	16.790	mg/L
TOC _{rem}	66.42	%
H ₂ O ₂ _{eff}	11.050	mg/L
H ₂ O ₂ _{res}	2	L
H ₂ O ₂ _{res}	1.8417	%

HRT	1 h	
Parameter	Value	Unit
Reactor Volume	1.5	L
TOC _{in}	50	mg/L
H ₂ O ₂	900	mg/L
pH	7	
Recycle ratio	0	0
Flow rate	24	ccm
	1.44	L/h
	36	%
HRT	1.04	h
TOC _{eff}	14.942	mg/L
TOC _{rem}	70.11	%
H ₂ O ₂ _{eff}	17.741	mg/L
H ₂ O ₂ _{res}	0	L
H ₂ O ₂ _{res}	1.9712	%

HRT	1 h	
Parameter	Value	Unit
Reactor Volume	1.5	L
TOC _{in}	50	mg/L
H ₂ O ₂	1200	mg/L
pH	7	
Recycle ratio	0	0
Flow rate	24	ccm
	1.44	L/h
	36	%
HRT	1.04	h
TOC _{eff}	15.4123	mg/L
TOC _{rem}	69.18	%
H ₂ O ₂ _{eff}	24.9570	mg/L
H ₂ O ₂ _{res}	2.0798	%

HRT	1 h	
Parameter	Value	Unit
Reactor Volume	1.5	L
TOC _{in}	50	mg/L
H ₂ O ₂	1500	mg/L
pH	7	
Recycle ratio	0	0
Flow rate	24	ccm
	1.44	L/h
	36	%
HRT	1.04	h
TOC _{eff}	17.8235	mg/L
TOC _{rem}	64.35	%
H ₂ O ₂ _{eff}	31.2043	mg/L
H ₂ O ₂ _{res}	2.0803	%

Appendix L. Photoreactor experimental design raw data of the effect of flow rate.

HRT	2.5 h	
<i>Parameter</i>	<i>Value</i>	<i>Unit</i>
Reactor Volume	1.5	L
TOC _{in}	50	mg/L
H ₂ O ₂	900	mg/L
pH	7	
Recycle ratio	0	
Flow rate	15	mL/min
	0.9	L/h
	22.5	%
HRT	1.67	h
TOC _{eff}	13.607	
	1	mg/L
TOC _{rem}	72.79	%
	14.901	
H ₂ O ₂ _{eff}	0	mg/L
H ₂ O ₂ _{res}	1.6557	%

HRT	1.25 h	
<i>Parameter</i>	<i>Value</i>	<i>Unit</i>
Reactor Volume	1.5	L
TOC _{in}	50	mg/L
H ₂ O ₂	900	mg/L
pH	7	
Recycle ratio	0	
Flow rate	45	mL/min
	2.7	L/h
	67.5	%
HRT	0.56	h
TOC _{eff}	14.716	
	6	mg/L
TOC _{rem}	70.57	%
	16.544	
H ₂ O ₂ _{eff}	5	mg/L
H ₂ O ₂ _{res}	1.8383	%

HRT	1.0 h	
<i>Parameter</i>	<i>Value</i>	<i>Unit</i>
Reactor Volume	1.5	L
TOC _{in}	50	mg/L
H ₂ O ₂	900	mg/L
pH	7	
Recycle ratio	0	
Flow rate	75	mL/min
	4.5	L/h
	112.5	%
HRT	0.33	h
TOC _{eff}	15.453	
	8	mg/L
TOC _{rem}	69.09	%
	17.356	
H ₂ O ₂ _{eff}	7	mg/L
H ₂ O ₂ _{res}	1.9285	%

HRT	50 min	
<i>Parameter</i>	<i>Value</i>	<i>Unit</i>
Reactor Volume	1.5	L
TOC _{in}	50	mg/L
H ₂ O ₂	900	mg/L
pH	7	
Recycle ratio	0	
Flow rate	105	mL/min
	6.3	L/h
	157.5	%
HRT	0.24	h
TOC _{eff}	16.656	
	7	mg/L
TOC _{rem}	66.69	%
	18.158	
H ₂ O ₂ _{eff}	9	mg/L
H ₂ O ₂ _{res}	2.0177	%

HRT	37.5 min	
<i>Parameter</i>	<i>Value</i>	<i>Unit</i>
Reactor Volume	1.5	L
TOC _{in}	50	mg/L
H ₂ O ₂	900	mg/L
pH	7	
Recycle ratio	0	
Flow rate	135	mL/min
	8.1	L/h
	202.5	%
HRT	0.19	h
TOC _{eff}	17.647	
	0	mg/L
TOC _{rem}	64.71	%
	18.823	
H ₂ O ₂ _{eff}	4	mg/L
H ₂ O ₂ _{res}	2.0915	%

HRT	30 min	
<i>Parameter</i>	<i>Value</i>	<i>Unit</i>
Reactor Volume	1.5	L
TOC _{in}	50	mg/L
H ₂ O ₂	900	mg/L
pH	7	
Recycle ratio	0	
Flow rate	165	mL/min
	9.9	L/h
	247.5	%
HRT	0.15	h
TOC _{eff}	18.838	
	1	mg/L
TOC _{rem}	62.32	%
	19.180	
H ₂ O ₂ _{eff}	0	mg/L
H ₂ O ₂ _{res}	2.1311	%

Appendix M. Photoreactor experimental design raw data of the effect of recycle ratio.

HRT	1 h	
Parameter	Value	Unit
Reactor Volume	1.5	L
TOC _{in}	50	mg/L
H ₂ O ₂	900	mg/L
pH	7	
Recycle ratio	0	0
Flow rate	24	ccm
	1.44	L/h
	36	%
HRT	1.04	h
TOC _{eff}	17.440	mg/L
TOC _{rem}	65.12	%
H ₂ O ₂ _{eff}	17.999	mg/L
H ₂ O ₂ _{res}	0	L
	2.00	%

HRT	1 h	
Parameter	Value	Unit
Reactor Volume	1.5	L
TOC _{in}	50	mg/L
H ₂ O ₂	900	mg/L
pH	7	
Recycle ratio	0.2	7
Flow rate	24	ccm
	1.44	L/h
	36	%
HRT	1.04	h
TOC _{eff}	15.093	mg/L
TOC _{rem}	9	%
H ₂ O ₂ _{eff}	69.81	%
H ₂ O ₂ _{res}	16.737	mg/L
	2	L
	1.86	%

HRT	1 h	
Parameter	Value	Unit
Reactor Volume	1.5	L
TOC _{in}	50	mg/L
H ₂ O ₂	900	mg/L
pH	7	
Recycle ratio	0.4	14
Flow rate	24	ccm
	1.44	L/h
	36	%
HRT	1.04	h
TOC _{eff}	14.857	mg/L
TOC _{rem}	9	L
H ₂ O ₂ _{eff}	70.28	%
H ₂ O ₂ _{res}	17.138	mg/L
	2	L
	1.90	%

HRT	1 h	
Parameter	Value	Unit
Reactor Volume	1.5	L
TOC _{in}	50	mg/L
H ₂ O ₂	900	mg/L
pH	7	
Recycle ratio	0.6	22
Flow rate	24	ccm
	1.44	L/h
	36	%
HRT	1.04	h
TOC _{eff}	16.3607	mg/L
TOC _{rem}	67.28	%
H ₂ O ₂ _{eff}	18.2455	mg/L
H ₂ O ₂ _{res}	2.03	%

HRT	1 h	
Parameter	Value	Unit
Reactor Volume	1.5	L
TOC _{in}	50	mg/L
H ₂ O ₂	900	mg/L
pH	7	
Recycle ratio	0.8	29
Flow rate	24	ccm
	1.44	L/h
	36	%
HRT	1.04	h
TOC _{eff}	18.6200	mg/L
TOC _{rem}	62.76	%
H ₂ O ₂ _{eff}	20.9680	mg/L
H ₂ O ₂ _{res}	2.33	%

Appendix N. Analysis of residuals in the photoreactor models.

Run	TOCin	Predicted TOCrem	Residuals	Block	Run	H2O2	Predicted TOCrem	Residuals	Block
2	10	80.43	0.00	80.43	12	300	60.15	0.00	60.15
3	25	69.21	-2.13	71.34	3	600	69.21	2.38	66.83
6	25	77.45	6.11		14	600	71.23	4.40	
8	25	71.94	0.60		18	600	67.09	0.26	
11	25	76.17	4.83		23	600	74.31	7.48	
14	25	71.23	-0.11		5	600	60.55	-6.28	
18	25	67.09	-4.25		16	600	66.79	-0.04	
23	25	74.31	2.97		20	600	68.77	1.94	
24	25	63.31	-8.03		22	600	56.72	-10.11	
4	40	71.90	3.44	68.46	2	900	80.43	10.28	70.15
7	40	71.96	3.50		4	900	71.90	1.75	
9	40	72.08	3.62		7	900	71.96	1.81	
12	40	60.15	-8.31		9	900	72.08	1.93	
15	40	64.70	-3.76		15	900	64.70	-5.45	
19	40	63.41	-5.05		19	900	63.41	-6.74	
21	40	72.31	3.85		21	900	72.31	2.16	
26	40	70.72	2.26		26	900	70.72	0.57	
27	40	66.89	-1.57		27	900	66.89	-3.26	
28	40	64.43	-4.03		29	900	72.81	2.66	
29	40	72.81	4.35		30	900	70.19	0.04	
30	40	70.19	1.73	10	900	64.39	-5.76		
1	55	66.12	0.80	65.32	6	1200	77.45	7.63	69.82
5	55	60.55	-4.77		8	1200	71.94	2.12	
13	55	66.83	1.51		11	1200	76.17	6.35	
16	55	66.79	1.47		24	1200	63.31	-6.51	
17	55	64.31	-1.01		1	1200	66.12	-3.70	
20	55	68.77	3.45		13	1200	66.83	-2.99	
22	55	56.72	-8.60		17	1200	64.31	-5.51	
25	55	72.44	7.12	25	1200	72.44	2.62		
10	70	64.39	0.00	64.39	28	1500	64.43	0.00	64.43

Run	Flow rate	Predicted TOCrem	Residuals	Block	Run	Recycle ratio	Predicted TOCrem	Residuals	Block
29	15	72.81	0.00	72.81	27	0	66.89	0.00	66.89
18	45	67.09	-2.88	69.97	23	0.2	74.31	4.74	69.57
23	45	74.31	4.34		20	0.2	68.77	-0.80	
20	45	68.77	-1.20		6	0.2	77.45	7.88	
22	45	56.72	-13.25		25	0.2	72.44	2.87	
6	45	77.45	7.48		3	0.2	69.21	-0.36	
11	45	76.17	6.20		16	0.2	66.79	-2.78	
13	45	66.83	-3.14		24	0.2	63.31	-6.26	
25	45	72.44	2.47		17	0.2	64.31	-5.26	
12	75	60.15	-8.92		69.07	29	0.4	72.81	
2	75	80.43	11.36	12		0.4	60.15	-9.52	
4	75	71.90	2.83	2		0.4	80.43	10.76	
7	75	71.96	2.89	4		0.4	71.90	2.23	
9	75	72.08	3.01	7		0.4	71.96	2.29	
19	75	63.41	-5.66	9		0.4	72.08	2.41	
21	75	72.31	3.24	21		0.4	72.31	2.64	
26	75	70.72	1.65	26		0.4	70.72	1.05	
27	75	66.89	-2.18	30		0.4	70.19	0.52	
30	75	70.19	1.12	10		0.4	64.39	-5.28	
10	75	64.39	-4.68	28		0.4	64.43	-5.24	
28	75	64.43	-4.64	15		0.4	64.70	-4.97	
3	105	69.21	2.53	66.68		18	0.6	67.09	0.01
14	105	71.23	4.55		22	0.6	56.72	-10.36	
5	105	60.55	-6.13		11	0.6	76.17	9.09	
16	105	66.79	0.11		13	0.6	66.83	-0.25	
8	105	71.94	5.26		14	0.6	71.23	4.15	
24	105	63.31	-3.37		5	0.6	60.55	-6.53	
1	105	66.12	-0.56		8	0.6	71.94	4.86	
17	105	64.31	-2.37		1	0.6	66.12	-0.96	
15	135	64.70	0.00	64.70	19	0.8	63.41	0.00	63.41

Run	TOCin	Predicted H2O2res	Residuals	Block	Run	H2O2	Predicted H2O2res	Residuals	Block
2	10	2.25	0.00	2.25	12	300	1.55	0.00	1.55
3	25	1.63	-0.32	1.95	3	600	1.63	-0.22	1.85
6	25	1.78	-0.17		5	600	1.96	0.11	
8	25	2.35	0.40		14	600	2.10	0.25	
11	25	1.87	-0.08		16	600	1.78	-0.07	
14	25	2.10	0.15		18	600	2.03	0.18	
18	25	2.03	0.08		20	600	1.71	-0.14	
23	25	1.36	-0.59		22	600	2.21	0.36	
24	25	2.48	0.53		23	600	1.36	-0.49	
4	40	1.82	-0.03	1.85	2	900	2.25	0.31	1.94
7	40	1.75	-0.10		4	900	1.82	-0.12	
9	40	1.75	-0.10		7	900	1.75	-0.19	
12	40	1.55	-0.30		9	900	1.75	-0.19	
15	40	2.11	0.26		10	900	2.35	0.41	
19	40	2.30	0.45		15	900	2.11	0.17	
21	40	1.77	-0.08		19	900	2.30	0.36	
26	40	1.77	-0.08		21	900	1.77	-0.17	
27	40	1.99	0.14		26	900	1.77	-0.17	
28	40	2.01	0.16		27	900	1.99	0.05	
29	40	1.61	-0.24		29	900	1.61	-0.33	
30	40	1.77	-0.08		30	900	1.77	-0.17	
1	55	2.03	0.05	1.98	1	1200	2.03	-0.05	2.08
5	55	1.96	-0.02		6	1200	1.78	-0.30	
13	55	1.79	-0.19		8	1200	2.35	0.27	
16	55	1.78	-0.20		11	1200	1.87	-0.21	
17	55	2.42	0.44		13	1200	1.79	-0.29	
20	55	1.71	-0.27		17	1200	2.42	0.34	
22	55	2.21	0.23		24	1200	2.48	0.40	
25	55	1.94	-0.04		25	1200	1.94	-0.14	
10	70	2.35	0.00	2.35	28	1500	2.01	0.00	2.01

Run	Flow rate	Predicted H2O2res	Residuals	Block	Run	Recycle ratio	Predicted H2O2res	Residuals	Block
29	15	1.61	0.00	1.61	27	0	1.99	0.00	1.99
6	45	1.78	-0.06	1.84	3	0.2	1.63	-0.26	1.89
11	45	1.87	0.03		6	0.2	1.78	-0.11	
13	45	1.79	-0.05		16	0.2	1.78	-0.11	
18	45	2.03	0.19		17	0.2	2.42	0.53	
20	45	1.71	-0.13		20	0.2	1.71	-0.18	
22	45	2.21	0.37		23	0.2	1.36	-0.53	
23	45	1.36	-0.48		24	0.2	2.48	0.59	
25	45	1.94	0.10		25	0.2	1.94	0.05	
2	75	2.25	0.33	1.92	2	0.4	2.25	0.37	1.88
4	75	1.82	-0.10		4	0.4	1.82	-0.06	
7	75	1.75	-0.17		7	0.4	1.75	-0.13	
9	75	1.75	-0.17		9	0.4	1.75	-0.13	
10	75	2.35	0.43		10	0.4	2.35	0.47	
12	75	1.55	-0.37		12	0.4	1.55	-0.33	
19	75	2.30	0.38		15	0.4	2.11	0.23	
21	75	1.77	-0.15		21	0.4	1.77	-0.11	
26	75	1.77	-0.15		26	0.4	1.77	-0.11	
27	75	1.99	0.07		28	0.4	2.01	0.13	
28	75	2.01	0.09		29	0.4	1.61	-0.27	
30	75	1.77	-0.15		30	0.4	1.77	-0.11	
1	105	2.03	-0.06	2.09	1	0.6	2.03	-0.01	2.04
3	105	1.63	-0.46		5	0.6	1.96	-0.08	
5	105	1.96	-0.13		8	0.6	2.35	0.31	
8	105	2.35	0.26		11	0.6	1.87	-0.17	
14	105	2.10	0.01		13	0.6	1.79	-0.25	
16	105	1.78	-0.31		14	0.6	2.10	0.06	
17	105	2.42	0.33		18	0.6	2.03	-0.01	
24	105	2.48	0.39		22	0.6	2.21	0.17	
15	135	2.11	0.00	2.11	19	0.8	2.30	0.00	2.30

Appendix O. Analysis of residuals in the biological processes models.

Run	TOCin	Predicted TOCrem	Residuals	Block
1	100	88.87	6.82	82.05
3	100	76.81	-5.24	
5	100	79.03	-3.02	
7	100	83.49	1.44	
9	550	80.01	1.78	78.23
10	550	70.49	-7.74	
11	550	75.09	-3.14	
12	550	76.34	-1.89	
13	550	80.83	2.60	
14	550	79.94	1.71	
15	550	80.45	2.22	
16	550	81.05	2.82	
17	550	79.83	1.60	
2	1000	70.80	0.04	70.76
4	1000	71.25	0.49	
6	1000	70.84	0.08	
8	1000	70.15	-0.61	

Run	Flow rate	Predicted TOCrem	Residuals	Block
1	45	88.87	10.18	78.69
2	45	70.80	-7.89	
9	45	80.01	1.32	
11	45	75.09	-3.60	
5	75	79.03	0.63	78.40
6	75	70.84	-7.56	
7	75	83.49	5.09	
8	75	70.15	-8.25	
13	75	80.83	2.43	
14	75	79.94	1.54	
15	75	80.45	2.05	
16	75	81.05	2.65	
17	75	79.83	1.43	
3	105	76.81	3.09	73.72
4	105	71.25	-2.47	
10	105	70.49	-3.23	
12	105	76.34	2.62	

Run	pH	Predicted TOCrem	Residuals	Block
5	5.0	79.03	3.94	75.09
6	5.0	70.84	-4.25	
9	5.0	80.01	4.92	
10	5.0	70.49	-4.60	
1	7.0	88.87	10.00	78.87
2	7.0	70.80	-8.07	
3	7.0	76.81	-2.06	
4	7.0	71.25	-7.62	
13	7.0	80.83	1.96	
14	7.0	79.94	1.07	
15	7.0	80.45	1.58	
16	7.0	81.05	2.18	
17	7.0	79.83	0.96	
7	9.0	83.49	7.22	76.27
8	9.0	70.15	-6.12	
11	9.0	75.09	-1.18	
12	9.0	76.34	0.07	

Run	TOCin	Predicted TN Crem	Residuals	Block
1	100	79.53	23.88	55.65
3	100	46.17	-9.48	
5	100	56.92	1.27	
7	100	39.98	-15.67	
9	550	51.04	-2.09	53.13
10	550	31.67	-21.46	
11	550	49.60	-3.53	
12	550	31.64	-21.49	
13	550	61.67	8.54	
14	550	62.27	9.14	
15	550	62.81	9.68	
16	550	63.45	10.32	
17	550	64.05	10.92	
2	1000	48.89	10.43	38.46
4	1000	45.25	6.79	
6	1000	25.36	-13.10	
8	1000	34.35	-4.11	

Run	Flow rate	Predicted TN Crem	Residuals	Block
1	45	79.53	22.27	57.27
2	45	48.89	-8.38	
9	45	51.04	-6.23	
11	45	49.60	-7.67	
5	75	56.92	4.60	52.32
6	75	25.36	-26.96	
7	75	39.98	-12.34	
8	75	34.35	-17.97	
13	75	61.67	9.35	
14	75	62.27	9.95	
15	75	62.81	10.49	
16	75	63.45	11.13	
17	75	64.05	11.73	
3	105	46.17	7.49	38.68
4	105	45.25	6.57	
10	105	31.67	-7.01	
12	105	31.64	-7.04	

Run	pH	Predicted TN Crem	Residuals	Block
5	5.0	56.92	15.67	41.25
6	5.0	25.36	-15.89	
9	5.0	51.04	9.79	
10	5.0	31.67	-9.58	
1	7.0	79.53	20.19	59.34
2	7.0	48.89	-10.45	
3	7.0	46.17	-13.17	
4	7.0	45.25	-14.09	
13	7.0	61.67	2.33	
14	7.0	62.27	2.93	
15	7.0	62.81	3.47	
16	7.0	63.45	4.11	
17	7.0	64.05	4.71	
7	9.0	39.98	1.09	38.89
8	9.0	34.35	-4.54	
11	9.0	49.60	10.71	
12	9.0	31.64	-7.25	

Run	TOCin	Predicted Biogas	Residuals	Block
1	100	94.02	-8.53	102.55
3	100	106.70	4.15	
5	100	103.24	0.69	
7	100	106.22	3.67	
9	550	104.28	-8.67	112.95
10	550	97.89	-15.06	
11	550	87.30	-25.65	
12	550	91.18	-21.77	
13	550	127.25	14.30	
14	550	125.13	12.18	
15	550	126.13	13.18	
16	550	129.01	16.06	
17	550	128.41	15.46	
2	1000	125.62	6.51	119.11
4	1000	104.28	-14.83	
6	1000	135.32	16.21	
8	1000	111.22	-7.89	

Run	Flow rate	Predicted Biogas	Residuals	Block
1	45	94.02	-8.79	102.81
2	45	125.62	22.82	
9	45	104.28	1.47	
11	45	87.30	-15.51	
5	75	103.24	-18.09	121.33
6	75	135.32	13.99	
7	75	106.22	-15.11	
8	75	111.22	-10.11	
13	75	127.25	5.92	
14	75	125.13	3.80	
15	75	126.13	4.80	
16	75	129.01	7.68	
17	75	128.41	7.08	
3	105	106.70	6.69	100.01
4	105	104.28	4.27	
10	105	97.89	-2.12	
12	105	91.18	-8.83	

Run	pH	Predicted Biogas	Residuals	Block
5	5.0	103.24	-6.94	110.18
6	5.0	135.32	25.14	
9	5.0	104.28	-5.90	
10	5.0	97.89	-12.29	
1	7.0	94.02	-24.49	118.51
2	7.0	125.62	7.11	
3	7.0	106.70	-11.81	
4	7.0	104.28	-14.23	
13	7.0	127.25	8.74	
14	7.0	125.13	6.62	
15	7.0	126.13	7.62	
16	7.0	129.01	10.50	
17	7.0	128.41	9.90	
7	9.0	106.22	7.24	98.98
8	9.0	111.22	12.24	
11	9.0	87.30	-11.68	
12	9.0	91.18	-7.80	

Run	TOCin	Predicted TSSres	Residuals	Block
1	100	18.62	-5.07	23.69
3	100	22.83	-0.86	
5	100	26.14	2.46	
7	100	27.15	3.47	
9	550	20.90	-4.18	25.08
10	550	30.31	5.23	
11	550	24.98	-0.10	
12	550	36.95	11.87	
13	550	22.52	-2.56	
14	550	21.71	-3.37	
15	550	22.10	-2.98	
16	550	22.92	-2.16	
17	550	23.35	-1.73	
2	1000	18.95	-11.33	30.28
4	1000	33.56	3.29	
6	1000	30.76	0.48	
8	1000	37.83	7.56	

Run	Flow rate	Predicted TSSres	Residuals	Block
1	45	18.62	-2.24	20.86
2	45	18.95	-1.91	
9	45	20.90	0.04	
11	45	24.98	4.12	
5	75	26.14	0.09	26.05
6	75	30.76	4.71	
7	75	27.15	1.10	
8	75	37.83	11.78	
13	75	22.52	-3.53	
14	75	21.71	-4.34	
15	75	22.10	-3.95	
16	75	22.92	-3.13	
17	75	23.35	-2.70	
3	105	22.83	-8.08	30.91
4	105	33.56	2.65	
10	105	30.31	-0.60	
12	105	36.95	6.04	

Run	pH	Predicted TSSres	Residuals	Block
5	5.0	26.14	-0.89	27.03
6	5.0	30.76	3.73	
9	5.0	20.90	-6.13	
10	5.0	30.31	3.28	
1	7.0	18.62	-4.33	22.95
2	7.0	18.95	-4.00	
3	7.0	22.83	-0.12	
4	7.0	33.56	10.61	
13	7.0	22.52	-0.43	
14	7.0	21.71	-1.24	
15	7.0	22.10	-0.85	
16	7.0	22.92	-0.03	
17	7.0	23.35	0.40	
7	9.0	27.15	-4.58	31.73
8	9.0	37.83	6.10	
11	9.0	24.98	-6.75	
12	9.0	36.95	5.22	

Appendix P. Combined anaerobic-aerobic UV/H₂O₂ processes reactor-modeling example.

Combined Anaerobic-Aerobic UV/H₂O₂ Processes

HRT (h)	S ₀ (mg/L)	S _f Experiments (mg/L)	S _f Model (mg/L)	ABR-AS-UV/H ₂ O ₂	ABR-AS-UV/H ₂ O ₂ Model	Error
0.00				1.00	1.00	
1.00	50.00	17.9986	16.3624	0.36	0.33	0.11%
2.00	50.00	6.3843	7.0936	0.13	0.14	0.02%
3.00	50.00	3.6105	3.2823	0.07	0.07	0.00%
4.00	50.00	1.4258	1.5842	0.03	0.03	0.00%
5.00	50.00	0.8665	0.7878	0.02	0.02	0.00%
6.00	50.00	0.3605	0.4006	0.01	0.01	0.00%
7.00	50.00	0.2280	0.2073	0.00	0.00	0.00%
8.00	50.00	0.0979	0.1088	0.00	0.00	0.00%
9.00	50.00	0.0636	0.0578	0.00	0.00	0.00%
10.00	50.00	0.0279	0.0310	0.00	0.00	0.00%
11.00	50.00	0.0184	0.0168	0.00	0.00	0.00%
12.00	50.00	0.0082	0.0091	0.00	0.00	0.00%
13.00	50.00	0.0055	0.0050	0.00	0.00	0.00%
14.00	50.00	0.0025	0.0028	0.00	0.00	0.00%
15.00	50.00	0.0017	0.0015	0.00	0.00	0.00%
16.00	50.00	0.0008	0.0009	0.00	0.00	0.00%
17.00	50.00	0.0005	0.0005	0.00	0.00	0.00%
18.00	50.00	0.0002	0.0003	0.00	0.00	0.00%
19.00	50.00	0.0002	0.0002	0.00	0.00	0.00%
20.00	50.00	0.0001	0.0001	0.00	0.00	0.00%
21.00	50.00	0.0001	0.0000	0.00	0.00	0.00%
22.00	50.00	0.0000	0.0000	0.00	0.00	0.00%
23.00	50.00	0.0000	0.0000	0.00	0.00	0.00%
24.00	50.00	0.0000	0.0000	0.00	0.00	0.00%

Appendix Q. Combined anaerobic-aerobic UV/H₂O₂ processes energy estimation.

t (min)	ABR	AS	UV/H ₂ O ₂	Overall consumption	
0.5	0.0368	0.8671	0.0001	0.9040	0.0014
2	0.0092	0.2168	0.0004	0.2264	0.0003
5	0.0037	0.0867	0.0010	0.0914	0.0001
10	0.0018	0.0434	0.0021	0.0473	0.0001
15	0.0012	0.0289	0.0031	0.0333	0.0000
20	0.0009	0.0217	0.0042	0.0268	0.0000
25	0.0007	0.0173	0.0052	0.0233	0.0000
30	0.0006	0.0145	0.0063	0.0213	0.0000
35	0.0005	0.0124	0.0073	0.0202	0.0000
40	0.0005	0.0108	0.0083	0.0196	0.0000
47	0.0004	0.0093	0.0097	0.0194	0.0000
50	0.0004	0.0087	0.0104	0.0195	0.0000
55	0.0003	0.0079	0.0115	0.0197	0.0000
60	0.0003	0.0072	0.0125	0.0200	0.0000
65	0.0003	0.0067	0.0135	0.0205	0.0000
70	0.0003	0.0062	0.0146	0.0210	0.0000
75	0.0002	0.0058	0.0156	0.0217	0.0000
80	0.0002	0.0054	0.0167	0.0223	0.0000
85	0.0002	0.0051	0.0177	0.0230	0.0000
90	0.0002	0.0048	0.0188	0.0238	0.0000
95	0.0002	0.0046	0.0198	0.0245	0.0000
100	0.0002	0.0043	0.0208	0.0254	0.0000
105	0.0002	0.0041	0.0219	0.0262	0.0000
110	0.0002	0.0039	0.0229	0.0270	0.0000
115	0.0002	0.0038	0.0240	0.0279	0.0000
120	0.0002	0.0036	0.0250	0.0288	0.0000
125	0.0001	0.0035	0.0260	0.0297	0.0000
130	0.0001	0.0033	0.0271	0.0306	0.0000
135	0.0001	0.0032	0.0281	0.0315	0.0000
140	0.0001	0.0031	0.0292	0.0324	0.0000
145	0.0001	0.0030	0.0302	0.0333	0.0000
150	0.0001	0.0029	0.0313	0.0343	0.0000

Appendix R. Combined anaerobic-aerobic UV/H₂O₂ processes overall treatment costs estimation.

TOC removal ABR-AS-UV	t (min)	Anaerobic bioreactor energy consumption	Overall Cost	ABR bioreactor	Aerobic bioreactor energy consumption	AS bioreactor	UV/H ₂ O ₂ photoreactor energy consumption	UV/H ₂ O ₂ photoreactor	Overall consumption	Overall Cost	Combined ABR-AS- UV/H ₂ O ₂		
17.41%	0.1	2.5751	0.2987	8.2976	0.0001	0.0000	0.0010	0.0001	0.0000	0.0121	2.5754	0.2987	5.9749
25.44%	0.5	0.5150	0.0597	1.6595	0.0005	0.0001	0.0050	0.0007	0.0001	0.0604	0.5163	0.0599	1.1977
34.24%	1	0.2575	0.0299	0.8298	0.0011	0.0001	0.0100	0.0014	0.0002	0.1208	0.2600	0.0302	0.6032
48.52%	2	0.1288	0.0149	0.4149	0.0022	0.0003	0.0199	0.0028	0.0003	0.2417	0.1337	0.0155	0.3103
59.38%	3	0.0858	0.0100	0.2766	0.0033	0.0004	0.0299	0.0042	0.0005	0.3625	0.0933	0.0108	0.2165
67.74%	4	0.0644	0.0075	0.2074	0.0043	0.0005	0.0398	0.0056	0.0007	0.4833	0.0743	0.0086	0.1725
74.24%	5	0.0515	0.0060	0.1660	0.0054	0.0006	0.0498	0.0070	0.0008	0.6042	0.0640	0.0074	0.1484
79.32%	6	0.0429	0.0050	0.1383	0.0065	0.0008	0.0598	0.0084	0.0010	0.7250	0.0579	0.0067	0.1343
83.33%	7	0.0368	0.0043	0.1185	0.0076	0.0009	0.0697	0.0098	0.0011	0.8458	0.0542	0.0063	0.1258
86.51%	8	0.0322	0.0037	0.1037	0.0087	0.0010	0.0797	0.0113	0.0013	0.9667	0.0521	0.0060	0.1209
89.04%	9	0.0286	0.0033	0.0922	0.0098	0.0011	0.0897	0.0127	0.0015	1.0875	0.0510	0.0059	0.1184
91.07%	10	0.0258	0.0030	0.0830	0.0109	0.0013	0.0996	0.0141	0.0016	1.2083	0.0507	0.0059	0.1176
92.70%	11	0.0234	0.0027	0.0754	0.0120	0.0014	0.1096	0.0155	0.0018	1.3292	0.0508	0.0059	0.1179
94.02%	12	0.0215	0.0025	0.0691	0.0130	0.0015	0.1195	0.0169	0.0020	1.4500	0.0514	0.0060	0.1192
95.08%	13	0.0198	0.0023	0.0638	0.0141	0.0016	0.1295	0.0183	0.0021	1.5708	0.0522	0.0061	0.1211
95.95%	14	0.0184	0.0021	0.0593	0.0152	0.0018	0.1395	0.0197	0.0023	1.6917	0.0533	0.0062	0.1236
96.66%	15	0.0172	0.0020	0.0553	0.0163	0.0019	0.1494	0.0211	0.0024	1.8125	0.0546	0.0063	0.1266
97.24%	16	0.0161	0.0019	0.0519	0.0174	0.0020	0.1594	0.0225	0.0026	1.9333	0.0560	0.0065	0.1299
97.71%	17	0.0151	0.0018	0.0488	0.0185	0.0021	0.1694	0.0239	0.0028	2.0542	0.0575	0.0067	0.1335
98.10%	18	0.0143	0.0017	0.0461	0.0196	0.0023	0.1793	0.0253	0.0029	2.1750	0.0592	0.0069	0.1373
98.42%	19	0.0136	0.0016	0.0437	0.0206	0.0024	0.1893	0.0267	0.0031	2.2958	0.0609	0.0071	0.1413
98.69%	20	0.0129	0.0015	0.0415	0.0217	0.0025	0.1992	0.0281	0.0033	2.4167	0.0627	0.0073	0.1455
98.90%	21	0.0123	0.0014	0.0395	0.0228	0.0026	0.2092	0.0295	0.0034	2.5375	0.0646	0.0075	0.1499
99.08%	22	0.0117	0.0014	0.0377	0.0239	0.0028	0.2192	0.0309	0.0036	2.6583	0.0665	0.0077	0.1544
99.23%	23	0.0112	0.0013	0.0361	0.0250	0.0029	0.2291	0.0323	0.0038	2.7792	0.0685	0.0079	0.1590
99.36%	24	0.0107	0.0012	0.0346	0.0261	0.0030	0.2391	0.0338	0.0039	2.9000	0.0706	0.0082	0.1637
99.46%	25	0.0103	0.0012	0.0332	0.0272	0.0032	0.2490	0.0352	0.0041	3.0208	0.0726	0.0084	0.1685
99.55%	26	0.0099	0.0011	0.0319	0.0282	0.0033	0.2590	0.0366	0.0042	3.1417	0.0747	0.0087	0.1733

TOC removal ABR-AS-UV	t (min)	Anaerobic bioreactor energy consumption	Overall Cost	ABR bioreactor	Aerobic bioreactor energy consumption	AS bioreactor	UV/H ₂ O ₂ photoreactor energy consumption	UV/H ₂ O ₂ photoreactor	Overall consumption	Overall Cost	Combined ABR-AS- UV/H ₂ O ₂		
99.62%	27	0.0095	0.0011	0.0307	0.0293	0.0034	0.2690	0.0380	0.0044	3.2625	0.0768	0.0089	0.1783
99.68%	28	0.0092	0.0011	0.0296	0.0304	0.0035	0.2789	0.0394	0.0046	3.3833	0.0790	0.0092	0.1833
99.73%	29	0.0089	0.0010	0.0286	0.0315	0.0037	0.2889	0.0408	0.0047	3.5042	0.0812	0.0094	0.1883
99.77%	30	0.0086	0.0010	0.0277	0.0326	0.0038	0.2989	0.0422	0.0049	3.6250	0.0834	0.0097	0.1934
99.81%	31	0.0083	0.0010	0.0268	0.0337	0.0039	0.3088	0.0436	0.0051	3.7458	0.0856	0.0099	0.1985
99.84%	32	0.0080	0.0009	0.0259	0.0348	0.0040	0.3188	0.0450	0.0052	3.8667	0.0878	0.0102	0.2037
99.86%	33	0.0078	0.0009	0.0251	0.0359	0.0042	0.3287	0.0464	0.0054	3.9875	0.0901	0.0104	0.2089
99.89%	34	0.0076	0.0009	0.0244	0.0369	0.0043	0.3387	0.0478	0.0055	4.1083	0.0923	0.0107	0.2142
99.90%	35	0.0074	0.0009	0.0237	0.0380	0.0044	0.3487	0.0492	0.0057	4.2292	0.0946	0.0110	0.2195
99.92%	36	0.0072	0.0008	0.0230	0.0391	0.0045	0.3586	0.0506	0.0059	4.3500	0.0969	0.0112	0.2248
99.93%	37	0.0070	0.0008	0.0224	0.0402	0.0047	0.3686	0.0520	0.0060	4.4708	0.0992	0.0115	0.2301
99.94%	38	0.0068	0.0008	0.0218	0.0413	0.0048	0.3786	0.0534	0.0062	4.5917	0.1015	0.0118	0.2355
99.95%	39	0.0066	0.0008	0.0213	0.0424	0.0049	0.3885	0.0548	0.0064	4.7125	0.1038	0.0120	0.2409
99.96%	40	0.0064	0.0007	0.0207	0.0435	0.0050	0.3985	0.0563	0.0065	4.8333	0.1061	0.0123	0.2463
99.96%	41	0.0063	0.0007	0.0202	0.0445	0.0052	0.4084	0.0577	0.0067	4.9542	0.1085	0.0126	0.2517
99.97%	42	0.0061	0.0007	0.0198	0.0456	0.0053	0.4184	0.0591	0.0069	5.0750	0.1108	0.0129	0.2571
99.97%	43	0.0060	0.0007	0.0193	0.0467	0.0054	0.4284	0.0605	0.0070	5.1958	0.1132	0.0131	0.2626
99.98%	44	0.0059	0.0007	0.0189	0.0478	0.0055	0.4383	0.0619	0.0072	5.3167	0.1155	0.0134	0.2680
99.98%	45	0.0057	0.0007	0.0184	0.0489	0.0057	0.4483	0.0633	0.0073	5.4375	0.1179	0.0137	0.2735
99.98%	46	0.0056	0.0006	0.0180	0.0500	0.0058	0.4583	0.0647	0.0075	5.5583	0.1203	0.0139	0.2790
99.99%	47	0.0055	0.0006	0.0177	0.0511	0.0059	0.4682	0.0661	0.0077	5.6792	0.1226	0.0142	0.2845
99.99%	48	0.0054	0.0006	0.0173	0.0521	0.0060	0.4782	0.0675	0.0078	5.8000	0.1250	0.0145	0.2900

Appendix S. Supplementary Materials.

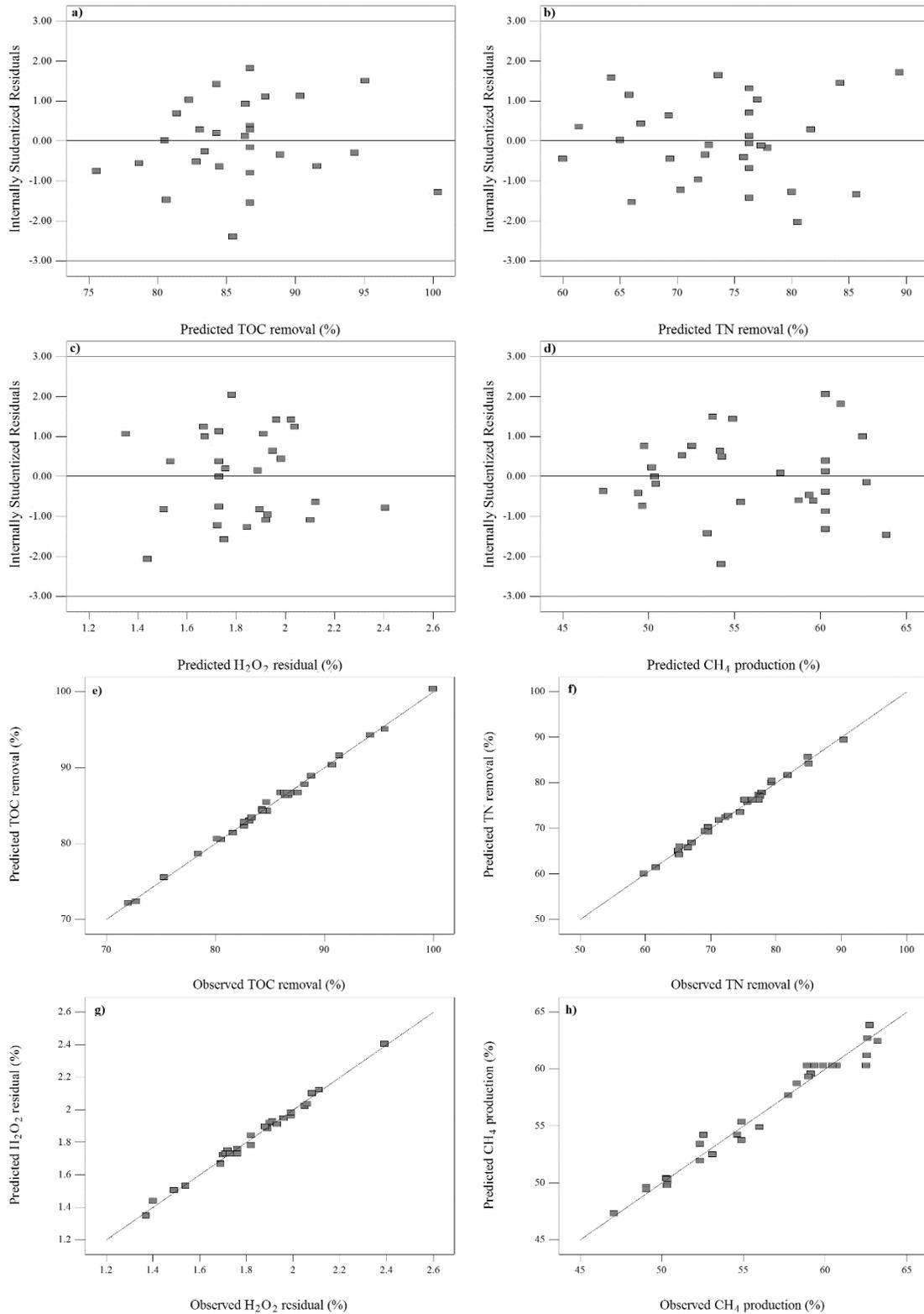


Figure S.1. Internally studentized residuals versus predicted values for the percental TOC removal, TN removal, H_2O_2 residual, and CH_4 production (a, b, c, and d, respectively); and model validation using experimental data for the percental TOC removal, percental TN removal, H_2O_2 residual, and CH_4 production (e, f, g, and h, respectively) in the combined ABR-AS-UV/ H_2O_2 processes. J. Environ. Manage. (2016), In Press.

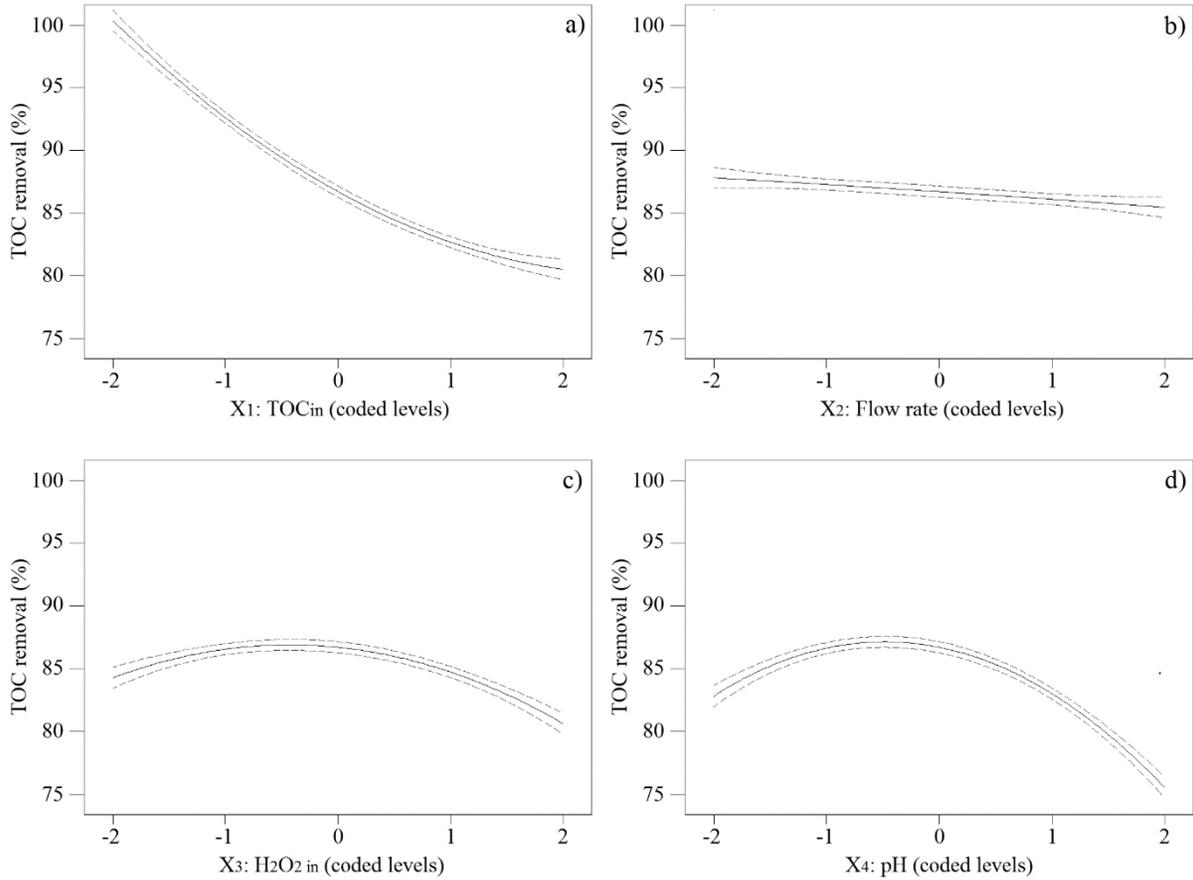


Figure S.2. The individual effect of model parameters on the percentual TOC removal: (a) influent concentration of TOC; (b) flow rate; (c) inlet H₂O₂ concentration; and (d) pH in the combined ABR–AS–UV/H₂O₂ processes. The continuous lines represent model predicted values; whereas the dashed lines represent the 95% confidence interval bands.

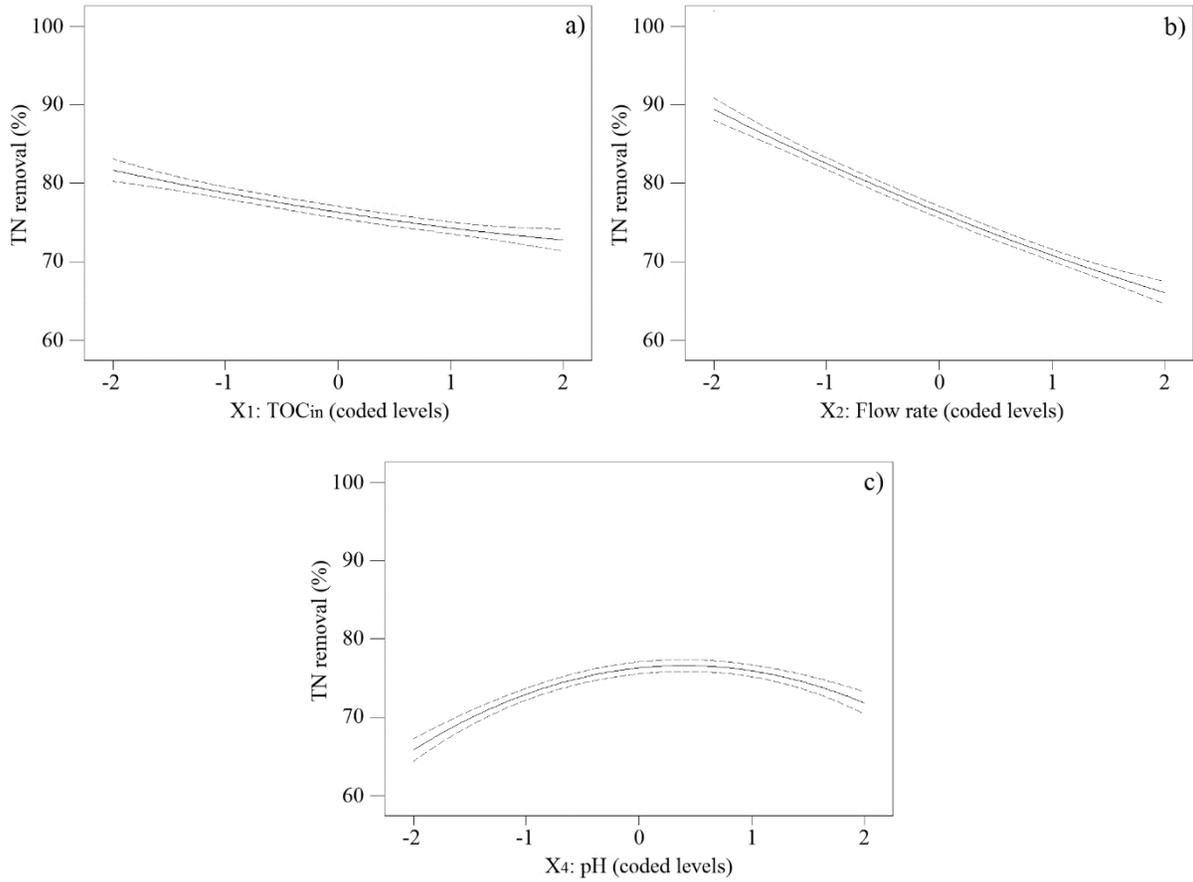


Figure S.3. The individual effect of model parameters on the percentual TN removal: (a) influent concentration of TOC; (b) flow rate; and (c) pH in the combined ABR–AS–UV/H₂O₂ processes. The continuous lines represent model predicted values; whereas the dashed lines represent the 95% confidence interval bands.

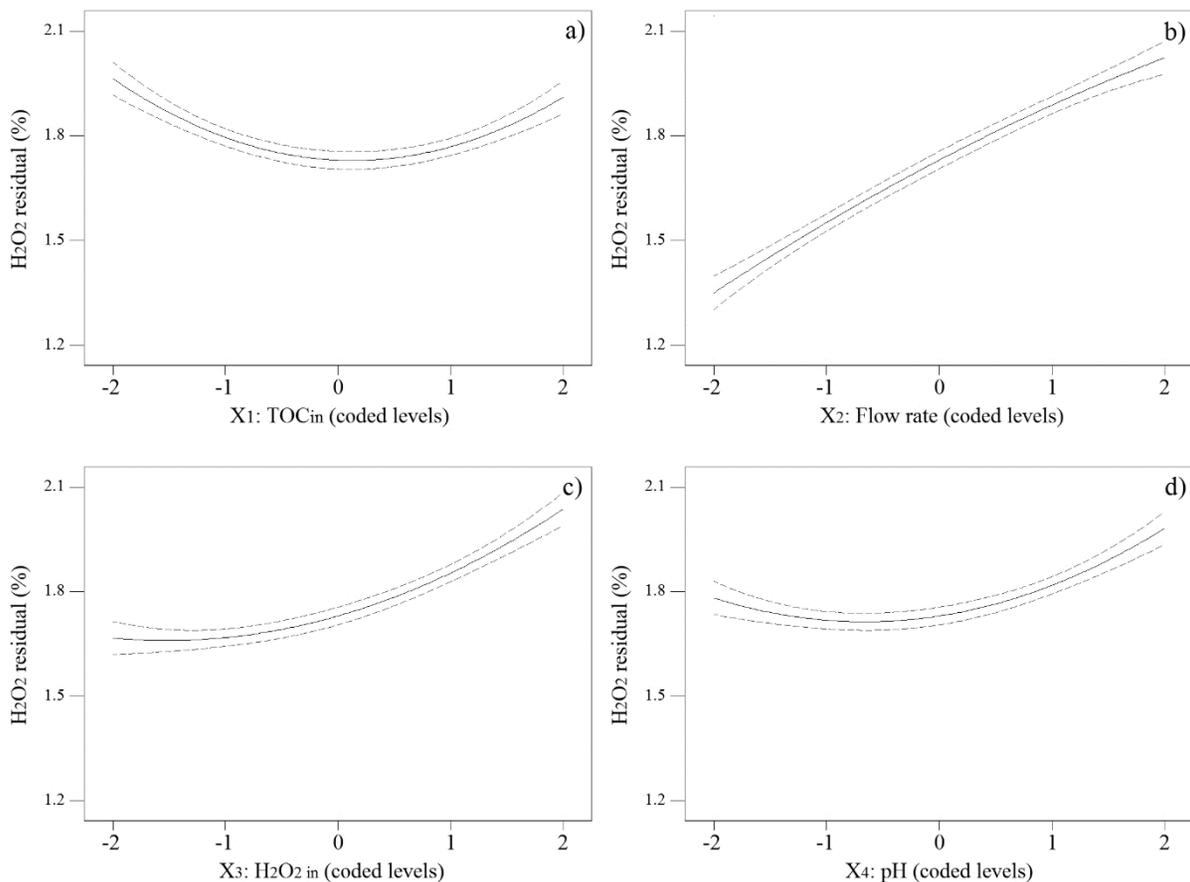


Figure S.4. The individual effect of model parameters on the percentual H_2O_2 residual: (a) influent concentration of TOC; (b) flow rate; (c) inlet H_2O_2 concentration; and (d) pH in the combined ABR–AS–UV/ H_2O_2 processes. The continuous lines represent model predicted values; whereas the dashed lines represent the 95% confidence interval bands.

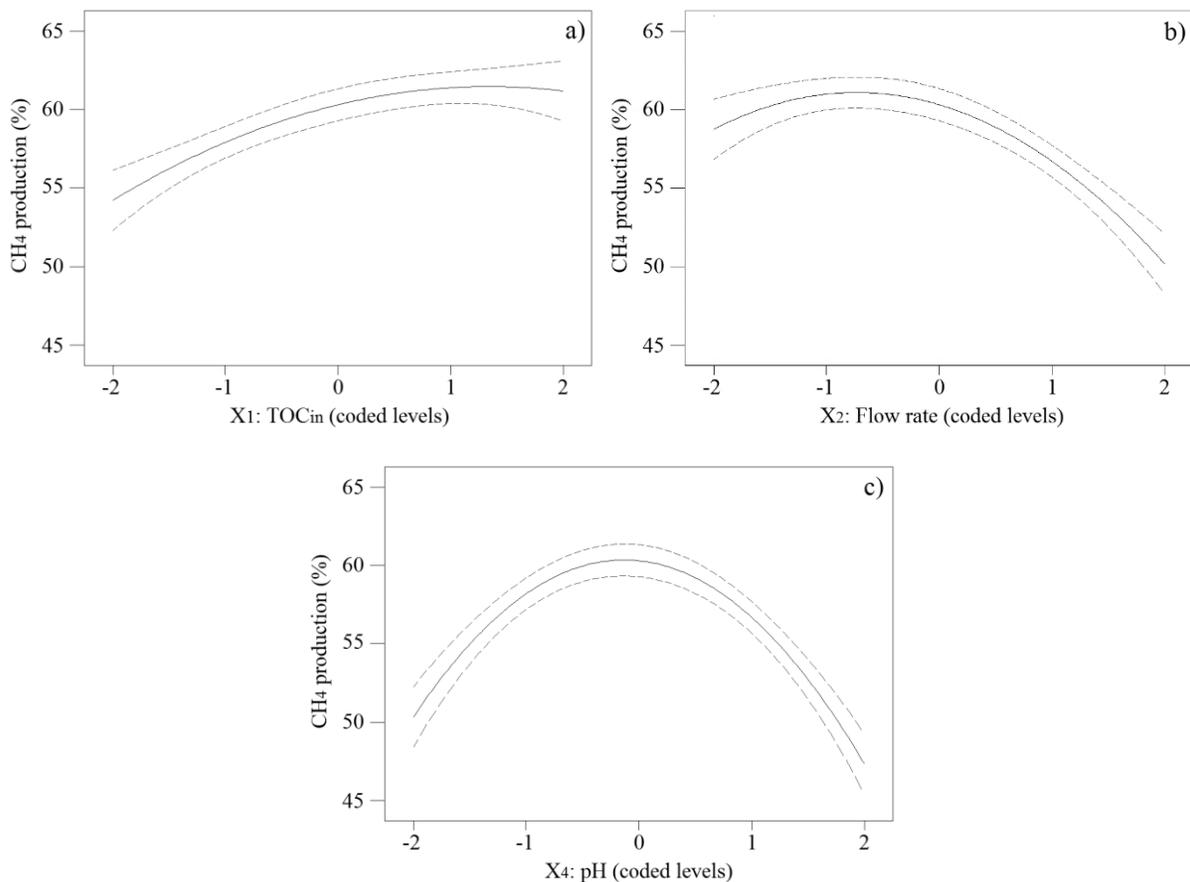


Figure S.5. The individual effect of model parameters on the CH₄ yield: (a) influent concentration of TOC; (b) flow rate; and (c) pH in the combined ABR–AS–UV/H₂O₂ processes. The continuous lines represent model predicted values; whereas the dashed lines represent the 95% confidence interval bands.

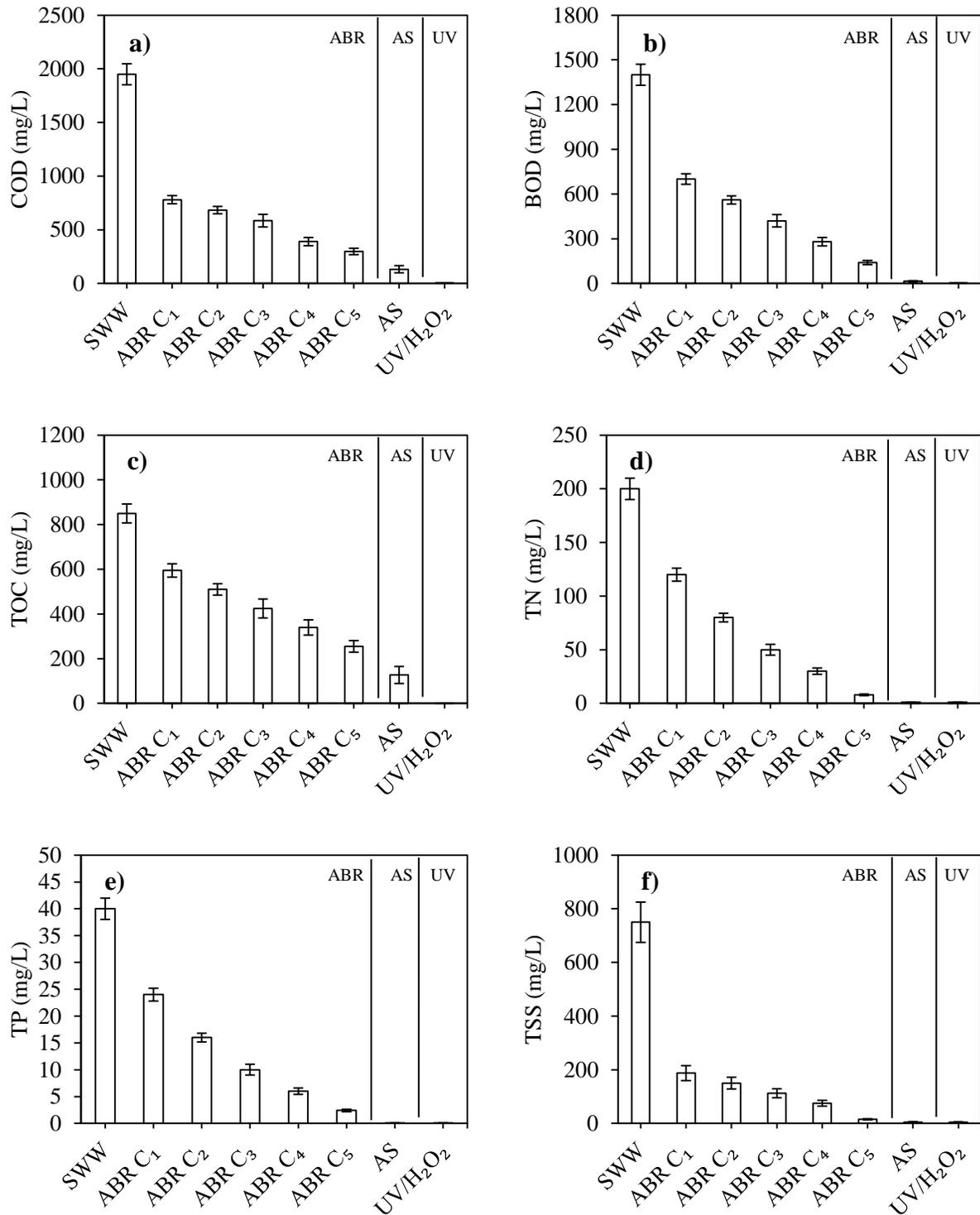


Figure S.6. Maximum remaining values of (a) COD, (b) BOD, (c) TOC, (d) TN, (e) TP, and (f) TSS from an actual slaughterhouse wastewater SWW using combined ABR-AS-UV/H₂O₂. Error bars represent the standard deviation of the experimental data.

Table S.1. Comparison of different technologies maximum efficiencies for slaughterhouse wastewater treatment from 2014 to 2016.

Method	HRT (h)	BOD_{in} (mg/L)	COD_{in} (mg/L)	TOC_{in} (mg/L)	TN_{in} (mg/L)	BOD_{rem} (%)	COD_{rem} (%)	TOC_{rem} (%)	TN_{rem} (%)	References
UST-AF-UF	144	-	3000	-	-	-	96	-	-	Abdurahman et al. (2015)
UST-AF-UF	144	-	3000	-	-	-	96	-	-	Abdurahman et al. (2015)
CW	28	-	468	-	61	-	60	-	46	Odong et al. (2015)
SBR	12	4240	6057	1436	576	-	93	-	93	Pan et al. (2015)
AOP	1	-	406	-	-	-	84	-	-	Paramo-Vargas et al. (2015)
SBR	3	-	8604	-	1493	-	80	-	88	Wosiack et al. (2015)
UST-AF-UF	343	-	5200	-	74	-	96	-	-	Abdurahman et al. (2016)
UF-RO	160	-	7970	-	-	-	80	-	-	Coskun et al. (2016)
AOP	2	340	-	94	55	-	-	81	-	Bustillo-Lecompte et al. (2016a)
ABR-AS	18	1339	1998	1694	255	84	89	89	79	Bustillo-Lecompte and Mehrvar (2016a)
ABR-AS-AOP	55	1635	2000	1200	841	100	99	100	85	Bustillo-Lecompte et al. (2016b)
ABR-AS-AOP	10	1831	2043	1691	866	100	99	100	90	Bustillo-Lecompte and Mehrvar (2016b)

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