Ryerson University
Digital Commons @ Ryerson

Theses and dissertations

1-1-2012

Combined anaerobic-aerobic and UV/H2O2 processes for the treatment of synthetic slaughterhouse wastewater

Ciro F. Lecompte
Ryerson University

Follow this and additional works at: http://digitalcommons.ryerson.ca/dissertations

 Part of the Environmental Sciences Commons

Recommended Citation
Lecompte, Ciro F., "Combined anaerobic-aerobic and UV/H2O2 processes for the treatment of synthetic slaughterhouse wastewater" (2012). *Theses and dissertations.* Paper 1276.

This Thesis is brought to you for free and open access by Digital Commons @ Ryerson. It has been accepted for inclusion in Theses and dissertations by an authorized administrator of Digital Commons @ Ryerson. For more information, please contact bcameron@ryerson.ca.

COMBINED ANAEROBIC-AEROBIC AND UV/H_2O_2 PROCESSES FOR THE TREATMENT OF SYNTHETIC SLAUGHTERHOUSE WASTEWATER

by

CIRO FERNANDO BUSTILLO LECOMPTE
B.Eng. in Civil Engineering
University of Cartagena, Cartagena, Colombia, 2008

A Thesis

presented to Ryerson University

in partial fulfilment of the requirements

for the degree of

Master of Applied Science
in the Program of
Environmental Applied Science and Management

Toronto, Ontario, Canada, 2012

© Ciro Fernando Bustillo Lecompte, 2012

AUTHOR'S DECLARATION FOR ELECTRONIC SUBMISSION OF A THESIS

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I authorize Ryerson University to lend this thesis to other institutions or individuals for the purpose of scholarly research.

I further authorize Ryerson University to reproduce this thesis by photocopying or by other means, in total or in part, at the request of other institutions or individuals for the purpose of scholarly research.

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

ABSTRACT

Combined Anaerobic-Aerobic and UV/H_2O_2 Processes for the Treatment of Synthetic Slaughterhouse Wastewater

Ciro Fernando Bustillo Lecompte
Master of Applied Science
Environmental Applied Science and Management
Ryerson University
2012

The biological treatment of a synthetic slaughterhouse wastewater (SSWW) was studied using an anaerobic baffled reactor (ABR) and an aerobic activated sludge (AS) at a laboratory scale, with total organic carbon (TOC) loading rates of 0.03–1.01 g/(L.day), total nitrogen (TN) loading rates of 0.01–0.19 g/(L.day), and a flow rate of 2.93 to 11.70 mL/min in continuous mode. Results revealed that combined anaerobic-aerobic processes had higher efficiency to treat SSWW than a single process. Up to 96.36% TOC, 80.53% TN, and 99.38% 5-day carbonaceous biochemical oxygen demand ($CBOD_5$) removal from an influent concentration of 1,008.85 mgTOC/L, 419.77 mgTN/L, and 640 mg$CBOD_5$/L at the hydraulic retention time (HRT) of 6.24 days and a flow rate of 3.75 mL/min was achieved. The UV/H_2O_2 process was studied to treat a secondary effluent of SSWW with TOC loadings of 64.88–349.84 mg/L. Up to 75.22% TOC and 84.38% $CBOD_5$ removal were obtained for an influent concentration of 64.88 mgTOC/L at the HRT of 3 h with H_2O_2 concentration of 900 mg/L. An optimum molar ratio dosage of 13.87 mgH_2O_2/mgTOC_{in} was also obtained. Combined anaerobic-aerobic and UV/H_2O_2 processes enhanced the biodegradability of the TOC, TN, and $CBOD_5$ present in the SSWW. Up to 99.98% TOC, 82.84% TN, and 99.69% $CBOD_5$ overall removals were obtained for an influent concentration of 1,004.88 mgTOC/L, 200.03 mgTN/L, and 640 mg$CBOD_5$/L at the HRT of 4 days and a flow rate of 5.90 mL/min. A cost-effectiveness analysis (CEA) was performed for the optimum conditions for the SSWW treatment by optimizing total electricity cost and HRT, in which the combined anaerobic-aerobic and UV/H_2O_2 processes had an optimal TOC removal of 92.46% at an HRT of 41 h, a cost of $1.25/kg of TOC removed, and $11.60/$m^3$ of treated SSWW. This process reaches a maximum TOC removal of 99% in 76.5 h with an estimated cost of $2.19/kg TOC removed and $21.65/$m^3$ treated SSWW.

Keywords: Synthetic slaughterhouse wastewater (SSWW); anaerobic baffled reactor (ABR); aerobic activated sludge (AS); UV/H_2O_2; TOC; TN; $CBOD_5$; combined processes.

ACKNOWLEDGMENTS

I would like to express my sincere gratitude to my supervisor, Dr. Mehrab Mehrvar, of the Department of Chemical Engineering at Ryerson University, for his guidance, assistance, and financial support throughout the successful completion of this research.

I would also like to acknowledge Dr. Lynda McCarthy and Dr. Ronald Pushchak, whose comments, advices and suggestions immensely benefitted this research; Dr. Michael Bardecki, Elias Chu, Isabella Fernandes, and Alison MacLeod, Ryerson University staff, for their support and guidance during my studies; Ali Hemmati, Daniel Boothe, and Tondar Tajrobehkar, Engineering Technologists of the Department of Chemical Engineering, for their technical support and assistance on my experimental setup and further experiments; Ashbridges Bay Wastewater Treatment Plant for providing the anaerobic and aerobic activated sludge essential for the processes used in this research; Adriana Gaona, Dinesh Patel, Masroor Mohajerani, Samira Ghafoori, Mauricio Barrera, and Weihua Cao for many times of enlightenment and entertainment, as well as their help in troubleshooting, support and advice.

The financial support of Natural Sciences and Engineering Research Council of Canada (NSERC) and Ryerson University is greatly appreciated.

Finally yet importantly, I would like to thank the professors of the University of Cartagena as follows: Dr. Edgar Quiñones, for his unconditional help and guidance; Monica Eljaiek, Dalia Moreno, Raul Guerrero Torres, Dr. Alfonso Arrieta and Dr. Javier Mouthon, whose advice and encouragement helped me to become a better person and professional. I would also like to show appreciation to my friends, mainly to Daisy, Juan Felipe, Maria Clara, Sylvia, Eder, Andrea, and Cinthia; my cousins Gustavo, Lucila, Lucy and David; my aunts and uncles; and my beloved mother, Candelaria, and my brother, Carlos, for their love, guidance, patience, understanding, sacrifice and invaluable support throughout my graduate studies. I also offer regards and greetings to all those who supported me in any way during the completion of this research and whose names were not mentioned.

TABLE OF CONTENTS

LIST OF TABLES

Page

LIST OF FIGURES

Page

NOMENCLATURE

A	pipe cross-sectional area (m^2)
Ae	aerobic
Ana	anaerobic
Anox	anoxic
c	speed of light (2.998×10^8 m/s)
$CBOD_{5,in}$	$CBOD_5$ concentration of influent wastewater sample (mg/L)
$CBOD_{5,out}$	$CBOD_5$ concentration of effluent wastewater sample (mg/L)
dn	denitrification
DO_0	dissolved oxygen of a diluted sample immediately taken after preparation (mg/L)
DO_f	dissolved oxygen of the sample after 5 days of incubation at 20C (mg/L)
dw	distilled water
E	Einstein unit, one mole (6.022×10^{23}) of photons, regardless of their frequency
E^o	standard electrode potential (V)
F	feed
f	ratio of the volume of Polyseed solution in glucose-glutamic acid (GGA)
G	biogas production (L/h)
g	growth
h	Planck's constant (6.626×10^{-34} J.s)
hv	quantum of radiation
HRT_{ABR}	hydraulic retention time of the ABR process (h)
HRT_{AS}	hydraulic retention time of the aerobic AS process (h)
HRT_{UV}	hydraulic retention time of the UV/H_2O_2 process (h)
k	reaction rate constant (1/M.s)
k_{C1}	first order rate coefficient of substrate in compartment 1 of the ABR
k_{Ci}	first order rate coefficient of substrate in compartment i of the ABR
$k_{s(\lambda)}$	specific rate of light absorption by TOC (E/mol.s)
K_{TOC}	half saturation constant
L	length that the flow is going through or around (diameter of the pipe or tube) (m)

met	methanogenic
n	nitrification
N	sample size
N_A	Avogadro's number (6.023×10^{23})
NLR_{Ae}	local nitrogen load in the aerobic zone (mgTN/L.h)
Q	flow rate of influent (L/h) (m^3/s)
q_0	incident photon irradiance ($E/cm^2.s$)
r	nominal radius of the photoreactor (cm)
Re	Reynolds number
R_i	inner radius of the photoreactor (cm)
rNdn	denitrification rate (mgN/L.h)
rNn	nitrification rate (mgN/L.h)
r_r	recycle rate in the ABR, which is a percent of the flow rate of the influent (%)
rTOC	overall total organic carbon removal rate (mgTOC/L.h)
$rTOC_{Ae}$	aerobic total organic carbon removal rate (mgTOC/L.h)
$rTOC_{Anox}$	total organic carbon removal rate by denitrification (mgTOC/L.h)
rTOCmet	methanogenic total organic carbon removal rate (mgTOC/L.h)
s	sample standard deviation
S_o	concentration of the substrate in the influent (mg/L)
S_1	concentration of the substrate in compartment 1 of the ABR (mg/L)
S_f	concentration of the substrate in the effluent (mg/L)
S_i	concentration of the substrate in compartment *i* of the ABR (mg/L)
S_{i-1}	concentration of the substrate in compartment *i-1* of the ABR (mg/L)
SC_1	dissolved oxygen of seed control before incubation (mg/L)
SC_2	dissolved oxygen of seed control after incubation (mg/L)
t	hydraulic retention time (s)
TN_o	initial concentration of total nitrogen (mg/L)
TOC_o	initial concentration of total organic carbon (mg/L)
TOC_{in}	TOC concentration of influent wastewater sample (mg/L)
TOC_{out}	TOC concentration of effluent wastewater sample (mg/L)
V	volume of the sample or reactor (L)
v	fluid velocity (m/s)
V_1	volume of the compartment 1 of the ABR (L)

V_{ABR}	volume of the ABR (L)
V_{Ae}	aerobic volume 1/5, 2/5 or 3/5 times *Vr* (L)
V_{AS}	volume of the aerobic AS reactor (L)
V_{BOD}	volume of a BOD bottle (mL)
V_i	volume of the compartment *i* of the ABR (L)
V_r	effective volume (L)
VSS_o	initial concentration of volatile suspended solids (mg/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)
W_4	sum of the weights of the solids of the sample and the dish after burning (mg)
X	specific growth rate of microorganisms
X_1	biomass concentration of substrate in compartment 1 of the ABR (mg/L)
XCH_4	methane molar fraction in biogas
XN_2	nitrogen molar fraction in biogas
X_i	biomass concentration of substrate in compartment *i* of the ABR (mg/L)
χ_i	observed values of the sample items ($\chi_1, \chi_2, \ldots, \chi_n$)
X_{max}	maximum specific growth rate of microorganisms
$\bar{\chi}$	mean value of the sample observations
%Nn	nitrification efficiency
%TN	overall total nitrogen removal efficiency
%TOC	overall total organic carbon removal efficiency

Greek Letters

α_λ	absorption coefficient (1/cm)
ε_λ	molar absorption coefficient of TOC (1/M.cm)
μ	dynamic viscosity of the fluid (for water at 25°C, $\mu = 8.98\times10^{-4}$ kg/m.s)
ρ	density of the fluid (1000 kg/m^3 for water at 25°C)
ϕ	quantum yield for TOC removal (mol/E)
Υ	cells yield coefficient

Acronyms

AAGBR	anaerobic-aerobic granular biofilm reactor
AAIBR	anaerobic-aerobic integrative baffled reactor
AASBR	anaerobic-anoxic sequencing batch reactor
ABFR	aerobic biofilm reactor
ACOT	aerobic contact oxidation tank
ABR	anaerobic baffled reactor
AdNR	anaerobic denitrifying reactor
AF	anaerobic filter
AFB	aerobic fluidized bed
AFFFBR	anaerobic fixed film fixed bed reactor
ALSR	airlift suspension reactor
AnaF	anaerobic filter
AnaFB	anaerobic fluidized bed
AOPs	advanced oxidation processes
ARB	aged-refuse biological reactor
ARSBFB	anaerobic reactor with sludge blanket and filter bed
AS	activated sludge
ASCS	aerobic solid contact system
BABS	batch aerobic biological system
BAC	biological activated carbon
BASR	biofilm airlift suspension reactor
BAT	best available technology economically achievable
BC MOE	British Columbia Ministry of Environment
BCDT	bubble column with a draught tube
BCR	bubble column reactor
BCT	best conventional pollutant control technology
BOCs	biodegradable organic compounds
BOD	biochemical oxygen demand
BOD_5	5-day biochemical oxygen demand
BPT	best practicable control technology available
$CBOD_5$	5-day carbonaceous biochemical oxygen demand

CC/EO	chemical coagulation/electrochemical oxidation
CDI	capacitive deionization
CEA	cost-effectiveness analysis
CEC	Council of the European Communities
CFU	colony-forming unit
COCs	chlorinated organic compounds
COD	chemical oxygen demand
CSOs	combined sewer overflows
CSSs	combined sewer systems
CSTRs	continuous stirred tank reactors
DAF	dissolved air flotation
DBPs	disinfection by-products
DI	deionization
DO	dissolved oxygen
ECO	Environmental Commissioner of Ontario
EEA	European Environment Agency
EGSB	expanded granular sludge bed
EHS	Environmental Health and Safety
EO	electrochemical oxidation
EOP	electrical oxidation potential
EU	European Union
EUV	extreme ultraviolet light; range from 121 nm to 10 nm
FBR	fixed bed biological reactor
FFB	fixed film bioreactor
FBNR	fixed bed nitrification reactor
FBP	fluidized biofilm process
FUV	far ultraviolet light; range from 200 nm to 122 nm
GRABBR	granular-bed anaerobic baffled reactor
HAD	heterotrophic-autotrophic denitrification
HB	hybrid bioreactor
HRT	hydraulic retention time
IAAFBR	integrated anaerobic-aerobic fluidized bed reactor
IAAFFR	integrated anaerobic-aerobic fixed film reactor

IBR	immobilised biomass reactor
IJC	International Joint Commission
LUV	low ultraviolet light; range from 100 nm to 88 nm
MBR	membrane bioreactor
MLSS	mixed liquor suspended solids (mg/L)
MLVSS	mixed liquor volatile suspended solids (mg/L)
MMHR	methanogenic-methanotrophic hybrid reactor
MPN	most probable number
MPP	meat and poultry products
MPPs	meat processing plants
MTE	mechanical thermal expression
MUV	middle ultraviolet light; range from 300 nm to 200 nm
NLR	nitrogen loading rate (mgTN/L.h)
NOM	natural organic matter
NSPS	new source performance standards
NUV	near ultraviolet light; range from 400 nm to 300 nm
OEB	Ontario Energy Board
OLR	organic loading rate (mgTOC/L.h)
O&M	operating and maintenance costs ($)
PAHs	polycyclic aromatic hydrocarbons
PC	packed column
PCE	tetrachloroethylene
PCP	personal care products
PCR	photochemical reactor
POME	palm oil mill effluent
PSES	pre-treatment standards for existing sources
PTA	purified terephthalic acid
RAAIBB	radial anaerobic-aerobic immobilized biomass bioreactor
RBC	rotating biological contactors
RO	reverse osmosis
SAAB	simultaneous aerobic and anaerobic bioreactor
SAAMB	staged anaerobic-aerobic membrane bioreactor
SBBR	sequencing biofilm batch reactor

SBR	sequencing batch reactors
SCF	seed correction factor (mg/L)
SFABR	split fed anaerobic baffled reactor
SSWW	synthetic slaughterhouse wastewater
SUV	super ultraviolet light; range from 150 nm to 10 nm
TAT	thermophilic aerobic treatment
TCE	trichloroethylene
THMs	trihalomethanes
TN	total nitrogen
TOC	total organic carbon
TSS	total suspended solids
UAAFBIR	upflow anaerobic-aerobic fixed bed integrated reactor
UASB	upflow anaerobic sludge bed-blankets
UBF	upflow bed filter
UN FAO	Food and Agriculture Organization of the United Nations
US	United States
US EPA	United States Environmental Protection Agency
UV	ultraviolet light
UVA	ultraviolet light of long wave (black light); range from 400 nm to 315 nm
UVB	ultraviolet light of medium wave; range from 315 nm to 280 nm
UVC	ultraviolet light of short wave or germicidal; range from 280 nm to 100 nm
VIS	visible light before UV spectrum
VSS	volatile suspended solids
VUV	vacuum ultraviolet light; range from 200 nm to 100 nm
WL	wetland

CHAPTER 1

INTRODUCTION

The increasing growth of the world's population has increased the pollution of freshwater due to the discharge of inadequately treated industrial and municipal wastewater. Along with industrial development, the problem increases daily, especially in developing countries (Amit and Rupali, 2004; Leitao et al., 2006; Krishna et al., 2009; Feng et al., 2009). For this reason, water and wastewater treatment has become very important for the continuing development of current society. Moreover, the progressively stricter standards for effluent discharge in North America and the European Union (EU) have made the developing of advanced wastewater treatment technologies necessary (Environment Canada, 2000; US EPA, 2004; World Bank Group, 2007). In addition, 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, and living standards of different countries and characteristics of water and its pollutants, many nations adopt diverse techniques for water and wastewater treatment.

Slaughterhouses produce large amounts of wastewater during the slaughtering process and periodic cleaning of residual particles. Although composition of slaughterhouse wastewaters varies based on the industrial process and water demand, these wastes usually contain high levels of organics with a large biochemical oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), and nitrogen and phosphorus from organic materials, including pieces of fat, grease, proteins, flesh, manure, grit, undigested feed, blood, hair and feathers (Camin, 1970; Bull et al., 1982; Sachon, 1982; Sachon, 1986; Sayed et al., 1988; Tritt and Schuchardt, 1992; Johns, 1995; Ruiz et al., 1997; Masse and Masse, 2000b; Sirianuntapiboon and Manoonpong, 2001; Matsumura and Mierzwa, 2008; Debik and Coskun, 2009).

Slaughterhouse wastewaters are typically treated in anaerobic reactors because of the high level of COD, which is used to measure the amount of organic compounds in water indirectly.

Nevertheless, anaerobic treatment methods have process instabilities including a low settling rate and the need for post-treatment of the noxious anaerobic effluent, which usually contains ammonium ions (NH_4^+), and hydrogen sulphide (HS^-) (Heijnen et al., 1991; Cao and Mehrvar, 2011). Although anaerobic treatment is efficient, complete stabilization of the organic matter is not possible by anaerobic treatment alone as the effluent produced by anaerobic treatment contains solubilised organic matters, which are more suited for treatment using aerobic processes or anaerobic–aerobic systems (Gray, 2005). For that reason, later post-treatment using aerobic treatment is necessary to meet the standards (Chan et al., 2009). Moreover, for the biological removal of nutrients (N and P), an adequate combination of anaerobic and aerobic processes is essential (Del Pozo and Diez, 2005).

According to Aggelis et al. (2001), neither anaerobic nor aerobic processes should be employed alone for efficient treatment, since aerobic or anaerobic treatment alone does not produce effluents that comply with effluent discharge limits when treating high organic strength wastewaters. The use of combined anaerobic-aerobic processes can also lead to a reduction in operating costs when compared with aerobic treatment alone (Vera et al., 1999), while simultaneously resulting in high organic matter removal efficiency and a smaller amount of aerobic sludge without pH correction. Benefits of the combined anaerobic-aerobic processes include potential resource recovery as anaerobic pre-treatment removes most of the organic pollutants and converts them into biogas and high overall treatment efficiency due to aerobic post-treatment (Frostell, 1983; Cervantes et al., 2006).

Biological treatment of wastewater is usually the most cost-effective technology (Pittier and Chudoba, 1990; Ruiz et al., 1997; Barber and Stuckey, 1999; Pulgarín et al., 1999; Masse and Masse, 2000b; Sarria et al., 2003; Al-Mutairi et al., 2008; Edalatmanesh et al., 2008; Krishna et al., 2009; Chan et al., 2009; Oller et al., 2011). However, industrial effluents and slaughterhouse wastewaters contain toxic and non-biodegradable organic substances, which make biological treatment alone insufficient (Steber and Wierich, 1986; Bowers et al., 1989; Adams et al., 1996; Pulgarín and Kiwi, 1996; García et al., 2001; Muñoz and Guieysee, 2006; Lapertot et al., 2006; Oller et al., 2011). As a result, advanced oxidation processes (AOPs) have been used to improve the biotreatability of wastewaters containing non-biodegradable organics, which are toxic to common microorganisms. AOPs are related to the production of hydroxyl radicals ($^{\bullet}OH$) (Balcioglu et al., 2001; Bhatkhande et al., 2002; Neyens and Baeyens, 2003; Gonze et al., 2003; Sarria et al., 2003; García-Montaño et al., 2006; Sarria et al., 2009), which have a very high oxidation potential and are able to oxidize almost

all organic pollutants (Gogate and Pandit, 2004a; Gogate and Pandit, 2004b; Devipriyas and Yesodharan, 2005; Pignatello et al., 2006; Pera-Titus et al., 2007; Comninellis et al., 2008; Shannon et al., 2008). Although these methods are very effective in wastewater treatment, they are expensive if applied alone. Therefore, a good alternative is to combine biological treatment and AOPs.

Objectives

The objectives of this study are to determine the efficiency of the combined anaerobic-aerobic and UV/H_2O_2 processes for the treatment of slaughterhouse wastewater; to evaluate the performance of a complementary aerobic treatment for biological nutrient removal by nitrification and denitrification; to evaluate the effectiveness and performance of different configurations of the combined processes, varying the number of phases and their order as a system; and to analyze the factors affecting its performance, the characteristics of slaughterhouse wastewater including its impacts on the environment and health effects, and the current standards and regulations for its discharge. In summary the objectives of the present study are:

1. To determine the performance and the treatment ability of the ABR, the aerobic AS, and the UV/H_2O_2 processes, as well as their combination in the removal of TOC, TN, and BOD from SSWW.
2. To evaluate the effects of hydraulic retention time (HRT) and influent concentrations of SSWW to the reactors on their performance.
3. To determine the optimal concentration of H_2O_2 and the optimum molar ratio dosage for TOC removal in a secondary effluent of SSWW.
4. To use a cost-effectiveness analysis (CEA) in order to determine the best alternative, by evaluating the total electricity cost, the effects of the HRT, the cost of H_2O_2 consumption, and the percentage of removal of TOC.

CHAPTER 2

LITERATURE REVIEW

2.1. Introduction

This chapter provides a comprehensive review of slaughterhouse wastewater treatment processes including anaerobic baffled reactors (ABR), aerobic activated sludge (AS), and UV/H_2O_2 as well as the factors affecting their performance and a description of their mechanisms. This chapter also reviews the characteristics, environmental impacts, health effects, and regulatory framework, including the current technologies, relevant to slaughterhouse wastewater.

2.2. Slaughterhouse wastewater characteristics

The treatment and disposal of wastewater from slaughterhouses and meat processing plants (MPPs) are an economic and public health necessity. The main source of slaughterhouse wastewater are the feces, urine, blood, lint, fat, carcasses, non-digested food in the intestines, the leftovers, the slop from the floors, utensils, the removal of bristles, storage of skins, the cleaning of bowels, guts room and laundry produced when slaughtering animals (Muñoz, 2005).

Slaughterhouse wastewater is considered detrimental worldwide due to its composition, characterized mostly by a complex mixture of fats, proteins and fibres (Camin, 1970; Bull et al., 1982; Sachon, 1982; Sachon, 1986; Sayed et al., 1988; Tritt and Schuchardt, 1992; Johns, 1995). Wastewaters from slaughterhouses and MPPs have been considered as an industrial waste in the category of agricultural and food industries and classified as one of the most harmful to the environment by the United States Environmental Protection Agency (US EPA) (Walter et al., 1974). Effluent discharge from slaughterhouses causes deoxygenation of rivers (Quinn and McFarlane, 1989) and contamination of groundwater (Sangodoyin and Agbawhe, 1992; Masse and Masse, 2000b). The organic matter concentration is medium to high and the residues are moderately solubilised, 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 (Bull et al., 1982; Ruiz et al., 1997; Masse and Masse, 2000b; Debik and

Coskun, 2009). High concentrations of BOD, COD and TSS in slaughterhouse wastewater containing flesh and blood have been reported to be 200,000, 375,000 and 2,800 mg/L or more, respectively (Tritt and Schuchardt, 1992; Masse and Masse, 2000a).

Several studies have described the common characteristics of slaughterhouse wastewater (Gariepy et al., 1989; Masse and Masse, 2000a; Seif and Moursy, 2001; Debik and Coskun, 2009; Cao, 2009; Cao and Mehrvar, 2011; Barrera, 2011; Barrera et al., 2011). These characteristics are summarized in Table 2.1, in which their common ranges and averages for slaughterhouse wastewater, including COD, TOC, BOD, TSS, TN, and pH among others are presented.

Table 2.1. Characteristics of slaughterhouse wastewater.

(Adapted from Debik and Coskun, 2009; Cao, 2009; Rajakumar et al., 2011; Barrera, 2011).

Parameter	Range	Average
TSS (mg/L)	300–2800	1164
COD (mg/L)	1250–15900	4221
BOD (mg/L)	610–1905	1209
$N\text{-}NH_4$ (mg/L)	14–169	41
$P\text{-}PO_4$ (mg/L)	1.30–80	19
Proteins (mg/L)	444–10000	2503
$N\text{-}NH_3$ (mg/L)	50–475	180
Oils and Greases (mg/L)	25–170	92
NOx (mg/L)	0.30–0.96	0.63
TN (mg/L)	50–785	427
Alkalinity (mg/L)	50–2100	450
TOC (mg/L)	100–1200	546
S-Sulphate/Sulphur (mg/L)	21–970	505
Temperature (°C)	n/a	35
pH	4.90–8.10	6.95
C/N	6.00–15	10

2.2.1. Slaughterhouse wastewater occurrence

Slaughterhouses are MPPs, where a variety of animals including cattle, hogs and poultry are slaughtered for human consumption and animal feeding operations (Wang et al., 2010). The meat processing industry is one of the major consumers of fresh water among industrial food processing facilities, as shown in Table 2.2, which makes it a significant producer of wastewater effluents. The World Bank classifies a slaughterhouse plant as a meat processing facility that may consume between 2.5 and 40 m^3 of water per metric tonnes of beef produced (World Bank, 1999).

Table 2.2. Fresh water consumption in different sectors of the US food and beverage manufacturing.
(Adapted from Wang et al., 2010).

Food Industry	%Water Consumption
Meat Processing	**23.9**
Beverages	12.7
Dairy	12.1
Other Food	10.9
Fruits and Vegetables	10.1
Bakery and Tortilla Products	9.6
Grain and Oilseeds	9.0
Sugar and Confectionary	5.2
Animal Food	4.9
Seafood	1.6

The production of beef has been growing steadily in recent years mostly in India and China due to income increases and the shift toward a western-like diet rich in proteins (Halweil, 2008). From 2002 to 2007, the global annual production of beef increased 14.7 million tonnes, representing an increase of 29% over 8 years (UN FAO, 2010). As a result, it can be inferred that the number of slaughterhouse facilities will get bigger, resulting in a greater volume of high-strength wastewater to be treated. Therefore, this growing industry will require reliable and effective technologies to treat these effluents properly before being discharged into source waters to minimize negative environmental impacts. Moreover, there is an additional problem specifically related to aging infrastructure, which may add to the potential risk of untreated wastewater reaching receiving waters. According to the International Joint Commission (IJC) (2009), the collection systems responsible for transporting wastewater to sewage treatment plants in some parts of North America were constructed back in the 19^{th} century and many of them have not been upgraded and are beyond the capacity for which they were originally designed. These collection systems have been designed to work as combined sewer systems (CSSs); therefore, domestic, commercial, industrial and storm-water are all transported through the same pipe connected to the water treatment facility.

The main problem of the CSSs is the overflow due to the wet-weather periods of heavy rainfall and snowmelt, when the pipes cannot handle the large volumes of water being driven into the system thereby exceeding its capacity, and resulting in a direct dumping of the combined raw sewage and storm-water into the receiving water bodies. As a result, massive loads of organic matter,

microorganisms and pathogens, chemicals, pharmaceuticals, and personal care products, as well as toxic and hazardous compounds from industrial sources could reach water bodies without proper treatment (Nemerow, 2007). Most of the remaining CSSs in North America are located in the Northeast part of the continent, particularly within the Great Lakes region. About 70% of the CSSs located in the US territory are found surrounding the Great Lakes. Meanwhile, in Canada, 20% of Ontario municipalities have CSSs representing a potential risk for overflow events to occur (IJC, 2009). According to the International Joint Commission (IJC) (2009), several Combined Sewer Overflow (CSO) events have been reported in the last decade near Great Lakes communities in Ontario. For instance, 107 confirmed CSOs with 1,544 releases of raw or partially treated sewage were reported in 2006. A recent report on pollutant sources affecting the Great Lakes stated that the CSO events are a major problem for the Saint Clair River water quality due to the constant discharges of raw sewage from the Sarnia sewer system during CSO events (USACE, 2004).

There are approximately 142 slaughterhouses in Ontario that can process a certain number of animals per day (Table 2.3). On-site treatment would be the best option to treat and disinfect the effluents, so they could then be discharged safely into receiving waters. Thus, the transportation of the water through the sewer system into the municipal wastewater treatment facilities would be avoided, minimizing the risk of raw water releases during overflow events. According to Wu and Mittal (2011), 53% of Ontario's slaughterhouses did not treat their wastewater prior to disposal (Figure 2.1). Only 16% of Ontario's slaughterhouses used dissolved air floatation (DAF) or aeration. The remaining 31% of slaughterhouses utilized passive systems such as storage tank or lagoon to settle solids. 6% of the slaughterhouses did not store the wastewater, and the drainage of these slaughterhouses was directly connected to the sewage treatment plant (STP). 80% of the slaughterhouses stored the wastewater in a retention tank prior to disposal and the remaining slaughterhouses stored the wastewater in lagoons or ponds. The sizes of these tanks varied from 3,000 to 750,000 L. 15% of the slaughterhouses disposed the wastewater at the STP. 9% of the slaughterhouses were directly connected to the STP and 6% of them used a hauler to haul the wastewater to the STP. 11% of the slaughterhouses used leaching bed for the disposal of the wastewater. An additional 21% used both the leaching bed and haulers to dispose of the wastewater. 43% of the slaughterhouses land applied the wastewater. Of the 43% that land applied, 33% of them used hauler to land apply the wastewater. 53% of them land applied the wastewater on premises and the remaining 14% land applied elsewhere.

Table 2.3. Provincially licensed meat plants in Ontario.

(Adapted from OMAFRA, 2011).

Plant Name	Address	City	Postal Code	Latitude	Longitude
Alvinston Custom Butchering Ltd.	3099 Broadway Street, PO Box 416	Alvinston	N0N1A0	42.8129	-81.8648
Brennan Poultry	7109 Mosside Line	Alvinston	N0N1A0	42.7330	-81.9368
Barron Poultry Limited	7470 Essex County Road 18	Amherstburg	N9V2Y7	42.0972	-83.0097
Domingos Meat Packers Ltd.	7396 W Garafraxa 3rd Line	Arthur	N0G1A0	43.8301	-80.4740
Abate Packers	7597 Jones Baseline	Arthur	N0G1A0	43.8231	-80.5240
Wellington Poultry Ltd.	7514 Wellington Road 109, RR 4	Arthur	N0G1A0	43.8358	-80.6158
Athens Meat Packers	63 Addison Road	Athens	K0E1B0	44.6448	-75.9105
Johnson Meats	RR 4, 49801 Glen Colin Line	Aylmer	N5H2R3	42.7925	-80.9691
Springwater Packers	RR 5, 9040 Springwater Rd.	Aylmer	N5H2R4	42.7665	-81.0311
Louro Bros. Meats Ltd.	RR 1, 1142 Reidsville Rd	Ayr	N0B1E0	43.2806	-80.4261
Beeton Meats	233 Patterson Street North, PO Box 208	Beeton	L0G1A0	44.0880	-79.7827
Belle Vallé Meats and Abattoir	982125 Belle Valle Road	Belle Valle	P0J1M0	47.6542	-79.6058
Valley Poultry Packers	3134 Main Street	Blezard Valley	P0M1E0	46.6095	-81.0688
Al Madina Halal Meat Packers	3944 County Road #1, RR 1	Brinston	K0E1C0	44.9285	-75.4208
Northern Quality Meats Ltd	290 Deplonty Road	Bruce Mines	P0R1C0	46.3331	-83.8539
The Chicken Coup	1302 Garage Road	Burk's Falls	P0A1C0	45.6358	-79.3083
Hay's Custom Cutting	2958 4th Line, RR 5	Campbellford	K0L1L0	44.3064	-77.6740
Ranchland Meats Ltd.	2021 Bruce Road #3, RR 1	Cargill	N0G1J0	44.1987	-81.2239
Hanson Meats	4643 Highway #3, RR 4	Cayuga	N0A1E0	42.9422	-79.8938
Tom Henderson Custom Meat Cutting	RR 2, 13200 McKenzie Rd.	Chesterville	K0C1H0	45.0279	-75.2063
Valtoudis Meat Packers	600 Concession 9, RR 6	Claremont	L1Y1A3	43.9602	-79.1860
Bilal Farms Inc.	1924 Landry	Clarence Creek	K0A1N0	45.4972	-75.2146
Whitmore Meat Packers Ltd.	3765 Line 12 N, RR 2	Coldwater	L0K1E0	44.6196	-79.5530
Desormeaux Meats Incorporated	1 Queen Street, PO Box 112	Crysler	K0A1R0	45.2187	-75.1536
Zehr's Country Market	70963 Bronson Line	Dashwood	N0M1N0	43.3351	-81.6341
Peel Sausage Inc.	RR 2	Drayton	N0G1P0	43.7008	-80.6812
Dresden Meat Packers Limited	R.R. #2, 78 Hwy, 10210 McCreary Line	Dresden	N0P1M0	42.6010	-82.1853
Hiview Packers	RR 1	Dundalk	N0C1B0	44.1262	-80.6028
Dundalk Poultry Processing	126815 Southgate Road 12	Dundalk	N0C1B0	44.1119	-80.3944
Hunters Dressed Meats	RR 8, 1834 Hutchinson Road	Dunnville	N1A2W7	42.9576	-79.5593
ENS Poultry Inc.	6424 8th Line Pilkington	Elora	N0B1S0	43.6385	-80.4673
Miedema's Meat Market Ltd.	129 Huron Street	Embro	N0J1J0	43.1550	-80.9014
Abattoir Brisson Ltd.	1100 St. André	Embrun	K0A1W0	45.2661	-75.3090
Rainy River District Regional Abattoir Inc.	Box 299, 26 Byng Street	Emo	P0W1E0	48.6362	-93.8371

Plant Name	Address	City	Postal Code	Latitude	Longitude
Miedema's Country Meats	41130 Thames Road East	Exeter	N0M1S5	43.3624	-81.4774
Rua Meats Ltd.	275 Frankford Road, RR 1	Foxboro	K0K2B0	44.2336	-77.4452
J.R. Meats	275 Frankford Road, RR 1	Foxboro	K0K2B0	44.2340	-77.4451
Agram 2005 Meats Inc.	10676 Trafalgar Road	Georgetown	L7G4S5	43.6191	-79.9142
L & M Meat Distributing	2487 14th Line	Gilford	L0L1R0	44.1965	-79.6001
Metheral Meats	RR 1, 9093 6/7 Nottawasaga Side Rd.	Glen Huron	L0M1L0	44.2954	-80.1874
The Burt Farm	1295 Tenth Line	Gore Bay	P0P1H0	45.9146	-82.3677
Schefter Poultry Processing	44783 Harriston Road	Gorrie	N0G1X0	43.8803	-81.0675
Sheik Halal Farms Inc.	193064 Amaranth East Luther Townline	Grand Valley	L0N1G0	43.8835	-80.2995
Wayne's Meat Products Inc.	RR 1, 8794 Indian Line	Hagersville	N0A1H0	42.9770	-80.0934
Lowbank Farms Ltd.	4510 Hwy 6	Hagersville	N0A1H0	42.9968	-80.0195
Bentinck Packers Limited	381488 Concession 4 NDR, RR 3	Hanover	N4N3B9	44.1957	-80.9812
Harriston Packing Co. Ltd.	142 Arthur Street	Harriston	N0G1Z0	43.9088	-80.8765
Metzger Meat Products	180 Brock Avenue	Hensall	N0M1X0	43.4365	-81.5115
Highgate Tender Meats Ltd.	14680 Hastings Line	Highgate	N0P1T0	42.5109	-81.8233
Town And Country Farms	13018 Steeles Avenue	Hornby	L0P1E0	43.5680	-79.8405
Everspring Farms Ltd.	22370 Adelaide Street North, RR 3	Ilderton	N0M2A0	43.0928	-81.2841
Miky's Smoke House	32 Hamann Road	Joques	P0L1R0	49.5974	-83.7449
Wallace Beef Inc.	3766 Hwy. 15	Joyceville	K0H1S0	44.3577	-76.3483
The Beef Way (1997)	RR 2, 2034 Hwy 21	Kincardine	N2Z2X4	44.2022	-81.5935
Lynch's Slaughterhouse	32 Holland Road, RR 1	Lansdowne	K0E1L0	44.4047	-75.9595
Gord's Abattoir Ltd.	643 Hwy 77, RR 5	Leamington	N8H3V8	42.1035	-82.6028
Abattoir LeFaivre	122 County Rd 15	Lefaivre	K0B1J0	45.6368	-74.8987
Len & Patti Butcher Block	2133 Little Britain Road	Lindsay	K9V4R2	44.3250	-78.7492
Cornell Meats	7086 Pack Road	London	N6P1M1	42.9256	-81.3181
Buchler Farms And Abattoir	186 Horner Rd.	Magnetawan	P0A1P0	45.4002	-79.3567
Weston Abattoir Ltd.	5409 North Talbot Road	Maidstone	N0R1K0	42.2303	-82.9382
Grey County Meats	RR 1	Maxwell	N0C1J0	44.3047	-80.4237
Elora Road Meats	RR 1	Mildmay	N0G2J0	44.0760	-81.1821
Ontario Halal Meat Packers	5593 Highway #25	Milton	L9T2X5	43.4826	-79.8266
Sargent Farms Ltd.	61 Garden Lane	Milton	L9T2P7	43.5134	-79.8854
Laplante Poultry Farms Ltd/Ferme Avicole Laplante Ltée	17141 Rombough Road	Monkland		45.1781	-74.8850
Mount Brydges Abattoir Ltd.	21618 Adelaide Road	Mount Brydges	N0L1W0	42.9036	-81.4381
Berube Poultry	10135 McIntyre Road	Mountain	K0E1S0	44.9916	-75.5033
Thunder Bay Meat Processing Company (1986) Limited	4754 Oliver Road	Murillo	P0T2G0	48.4212	-89.4712
Bearbrook Farm Abattoir	8411 Russell Road, RR 3	Navan	K4B1J1	45.3824	-75.3536
Clement Poultry & Sons	85 Lovekin Road, RR 8	Newcastle	L1B1L9	43.9097	-78.6153

Plant Name	Address	City	Postal Code	Latitude	Longitude
Newmarket Meat Packers Ltd.	15452 Warden Avenue	Newmarket	L3Y9E5	44.0262	-79.3716
Norwich Packers Limited	11 Robson Street	Norwich	N0J1P0	42.9775	-80.5983
Hilts Butcher Shop Ltd.	1948 7th Line, Asphodel, RR 3	Norwood	K0L2V0	44.3479	-77.9986
Manilla Halal Meats	18619 Simcoe St.	Oakwood	K0M2M0	44.3269	-78.9957
Gerald Gemus & Sons Ltd.	6130 Snake Lane	Oldcastle	N0R1L0	42.2106	-82.9411
Morrison Custom Poultry Processing Ltd.	3711 Lindsay Highway, RR 3	Omemee	K0L2W0	44.2925	-78.5882
Matar Meats	2690 Stagecoach Rd., RR 1	Osgoode	K0A2W0	45.1916	-75.5683
Hafiz Halal Poultry Inc.	116 Bloor Street East	Oshawa	L1H3M2	43.8815	-78.8516
Country Meadow Meats	122242 Sideroad 12, RR 3	Owen Sound	N4K5N5	44.5323	-80.9885
Ideal Meat Packers Ltd.	RR 4	Owen Sound	N4K5N6	44.5650	-80.9273
Griffiths Country Meats	60 Griffiths Road	Oxdrift	P0V2J0	49.8059	-93.0041
Wall's Pork Shop	178 Wall Street	Oxdrift	P0V2J0	49.7557	-92.9929
Mr. Beef	223 McWatty Road	Pakenham	K0A2X0	45.1919	-76.1749
Mcgarroch Of Micksburg Custom Butchering	2749 Micksburg Rd., RR 3	Pembroke	K8A6W4	45.6768	-77.0548
Reiche Meat Products Ltd.	555 Reiche Rd., RR 3	Pembroke	K8A6W4	45.6689	-77.1038
Smokey Joe's	7949 Hwy #7	Peterborough	K9J6X3	44.3114	-78.4334
Otonabee Meat Packers Ltd.	RR 7, 2043 Drummond Line	Peterborough	K9J6X4	44.2906	-78.2413
Weiland Meats Ltd.	340 Centre Street	Petrolia	N0N1R0	42.8855	-82.1483
Cole Bros. Meat Processing	134 Old Milford Rd, RR 9	Picton	K0K2T0	43.9986	-77.1093
Hank Dekoning Limited	RR 1, 1768 Hwy #6	Port Dover	N0A1N3	42.8191	-80.1497
Prime Cut Meats	4311 Mastwood Road	Port Hope	L1A3V7	43.9841	-78.3897
Windcrest Meat Packers	1350 Scugog - 3rd Line	Port Perry	L9L1B3	44.0520	-78.9590
Bill's Turkey Farm Ltd.	2978 Holborn Rd.	Queensville	L0G1R0	44.1698	-79.4067
Bennett Abattoir	1984 Hwy, 572	Ramore	P0K1R0	48.4655	-80.3179
Town and Country Meats and Abattoir	19950 Hill Road	Ridgetown	N0P2C0	42.4259	-81.8702
Taylor's Custom Meats	11544 Northumberland Rd. 29, RR 4	Roseneath	K0K2X0	44.1406	-78.0581
Russell Slaughter House	424 Castor Street	Russell	K4R1E5	45.2643	-75.3398
Doug's Meats	RR 3	Schomberg	L0G1T0	43.9643	-79.6924
J J Meat Distributing Inc.	14600 10th Concession, RR 3	Schomberg	L0G1T0	43.9339	-79.6859
Fiore Game Farm	7255 Highway #9, RR 1	Schomberg	L0G1T0	44.0009	-79.7194
Pine Ridge Packers (2003)	Lot 6, Conc 5, Durham Region	Scugog Twp	L0B1B0	44.1094	-78.8643
King Capon Ltd.	18347 Warden Avenue	Sharon	L0G1V0	44.0980	-79.3850
Horizon Meat Packers Inc.	Con 7 E Pt Lot 27, Farm #335424	Shelburne	L0N1S5	44.0450	-80.2690
V. G. Packers Limited	RR 5, 966 Woollen Mill Rd	Simcoe	N3Y4K4	42.8460	-80.2210
Townsend Butchers Inc.	RR 4, 419 Conc. 14	Simcoe	N3Y4K3	42.8636	-80.2755
Rideau Meats	12090 Highway 15, RR 6	Smith Falls	K7A4S7	44.9271	-76.0281
Sanabil Halal Meat Farm	5309 Spring Creek Road	Smithville	L0R2A0	43.1036	-79.4882

Plant Name	Address	City	Postal Code	Latitude	Longitude
A.S. Poultry	7611 Kimbo Road	Smithville	L0R2A0	43.1245	-79.6085
Sprucedale Quality Meats Inc.	RR 1, 438 Fourth Avenue	Sprucedale	P0A1Y0	45.4378	-79.4377
Julius Meat Packers Inc.	2340 Patterson Road, RR 1	St. Ann's	L0R1Y0	43.0776	-79.5256
Kingma Meat Products Limited	1150 Regional Road 27 - RR 2	St. Ann's	L0R1Y0	43.0221	-79.5014
CRO Quail Farms Inc.	3625 Sixteen Road	St. Ann's	L0R1Y0	43.0787	-79.5256
Reist & Weber Butchering Custom Killing & Whole Sales Pork	RR 1	St. Jacobs	N0B2N0	43.5447	-80.5730
Norfolk Packers	RR 2, 4051 Lakeshore Road	St. Williams	N0E1P0	42.6599	-80.4340
Joe Savage & Fils Abattoir Inc.	C.P. 28 - 113 Rue Principale	St-Albert	K0A3C0	45.2546	-75.1242
Stayner Meat Packers Ltd.	352 Warrington Road	Stayner	L0M1S0	44.4062	-80.0600
Hastings County Meat Packers Inc.	570 Moira Rd, RR 2	Stirling	K0K3E0	44.3441	-77.4531
Highland Packers Ltd.	432 Highland Road East	Stoney Creek	L8J3G4	43.1348	-79.7538
King Cole Ducks Ltd.	15336 Warden Avenue	Stouffville	L4G3H3	44.0251	-79.3712
Ralph Bos Meats Ltd.	3742 Egremont Drive	Strathroy	N7G3H6	43.0052	-81.6178
Lindsay Zabiha Meat Packer	S1255 Durham Road #13	Sunderland	L0C1H0	44.2290	-79.0423
Blackwater Halal meat Ltd.	S1255 Durham Road 13	Sunderland	L0C1H0	44.2290	-79.0423
Mogk's Butcher Shop	RR 2, 516702 East Zorra	Tavistock	N0B2R0	43.2702	-80.8482
Tilbury Abattoir	4049 Bonneau Line	Tilbury	N0P2L0	42.2708	-82.3887
Cargill Foods Toronto	71 Rexdale Blvd	Toronto	M9W1P1	43.7131	-79.5611
St Ann's Foods Inc.	145 Bethridge Rd	Toronto	M9W1N4	43.7073	-79.5819
Cmp Meats	2255 St Clair Ave W	Toronto	M6N1K8	43.6703	-79.4777
Quality Meat Packers Limited	2 Tecumseth St, Suite 1	Toronto	M5V2R5	43.6408	-79.4044
Corsetti Meat Packer Limited	2255 St Clair Ave W	Toronto	M6N1K8	43.6703	-79.4777
Meat Express	328 Passmore Ave, Unit 2	Toronto	M1V3N8	43.82.81	-79.2627
Maple Leaf Foods Inc.	550 Kipling Ave	Toronto	M8Z5E9	43.6144	-79.5242
N & H Food Co Limited	125 Union St, Unit 2	Toronto	M6N3N4	43.6796	-79.4683
Maple Leaf Foods Inc.	30 St Clair Ave W, Suite 1500	Toronto	M4V3A1	43.6879	-79.3951
Elbee Meat Packers Limited	1 Glen Scarlett Rd	Toronto	M6N1P4	43.6747	-79.4730
Kam Li Food Co Ltd	229 Broadview Ave	Toronto	M4M2G7	43.6621	-79.3512
International Food Centre Ltd	1415 Bloor St W	Toronto	M6P3L4	43.6572	-79.4476
1243275 Ontario Inc.	33 Terry Dr	Toronto	M6N3T4	43.6732	-79.4832
Genesis Meat Packers Inc.	70 Glen Scarlett Rd	Toronto	M6N1P4	43.6746	-79.4740
Dean Butcher Shop	30 Dean Park Rd	Toronto	M1B5S6	43.8039	-79.1696
Northern Meat Packers and Abattoir Ltd.	266 McFadden Line, Box 175	Trout Creek	P0H2L0	45.9610	-79.3787
Willie's Meats Ltd.	2387 4th Conc. West, RR 1	Troy	L0R2B0	43.2789	-80.2013
Palmateer's Abattoir Ltd.	2553 River Street West	Tweed	K0K3K0	44.4697	-77.3302
Vanessa Meats & Deli Inc.	RR 3, 1728 Reg. Rd. #19	Vanessa	N0E1V0	42.9684	-80.3873
Walkerton Meat Market	963 Old Durham Road	Walkerton	N0G2V0	44.1363	-81.1349

Plant Name	Address	City	Postal Code	Latitude	Longitude
Country Poultry Processing	RR 2	Wallenstein	N0B2S0	43.6718	-80.6733
Bachert Meats Inc. (2006)	RR 1, 43181 Blyth Road	Walton	N0K1Z0	43.6667	-81.2795
Creative Meats	RR 1	Warren	P0H2N0	46.4513	-80.3995
Millgrove Packers Limited	RR 2, 549 Conc. 5 W.	Waterdown	L0R2H2	43.3333	-79.9816
Lloyd Miedema & Sons	RR 5, 1812 Thompson Road East	Waterford	N0E1Y0	42.9428	-80.1709
Niagara Sausage & Meat Products Limited	RR 4, Ridge Road	Welland	L3B5N7	42.9753	-79.2184
Aman's Abattoir	286 Main Street, PO Box 177	Wellington	K0K3L0	43.9520	-77.3516
Charles Quality Meats	RR 1	Wilmot	N0B2L0	43.4487	-80.6247
Green's Meat Market And Abattoir Ltd.	237 Arthur Street	Wingham	N0G2W0	43.8973	-81.3130
Ewedell Farms	1282 Oriole Park Drive	Woodslee	N0R1V0	42.2318	-82.7367
Lambton Meat Products	5814 Minielly Road	Wyoming	N0N1T0	42.9808	-82.0934
Brian Quinn's Meats Ltd.	3987 County Rd. #1, RR 2	Yarker	K0K3N0	44.3620	-76.7770

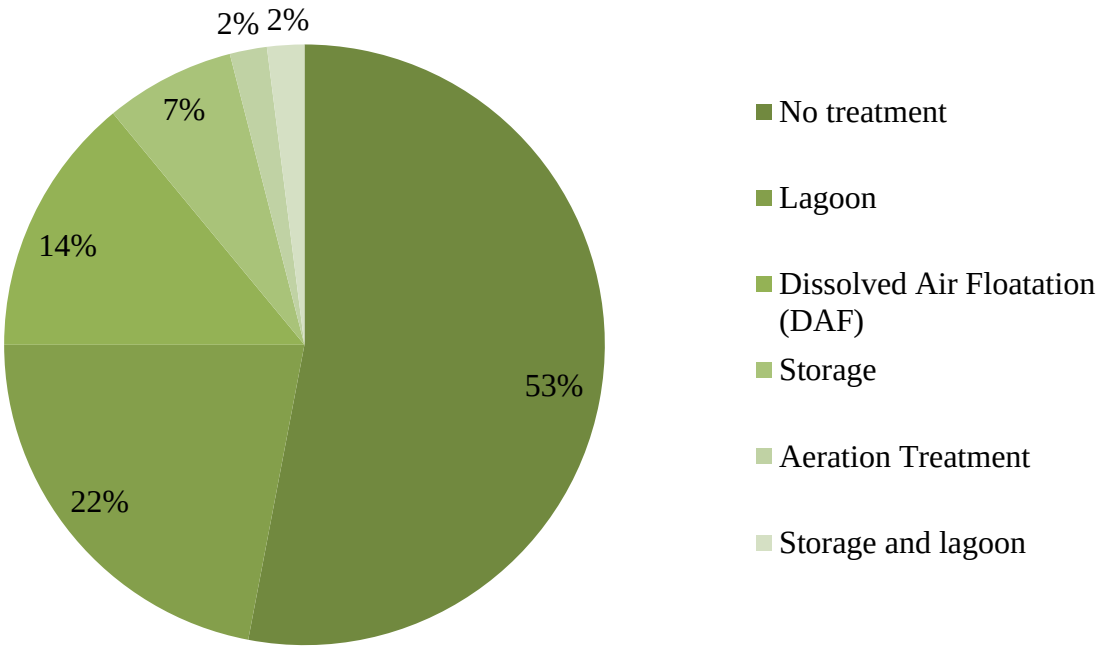


Figure 2.1. Wastewater treatment methods used by slaughterhouses.
(Adapted from Wu and Mittal, 2011).

2.2.2. Slaughterhouse wastewater guidelines and regulations

Regulations and guidelines are essential components in dealing with the environmental impact of slaughterhouse industries. The treatment systems developed by industry are frequently regarded as a regulatory obligation, increasing capital and running costs, and yielding negative economic returns. Compliance with environmental legislation should not necessarily lead to the creation of additional costs, but can instead provide a secondary source of income. The standards and regulations governing slaughterhouses vary considerably around the world. In many countries, the slaughter of animals is regulated by custom and tradition rather than by law. Two main kinds of meat processing systems are available, one that is produced in modern mechanized slaughterhouses and the other from local butcher shops.

The selection of a particular treatment depends on the characteristics of the wastewater, the available technology, and the 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 (Tchobanoglous et al., 2003). The main factors determining whether a plant can discharge into the 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).

A major concern with MPP' effluent is related to the discharge of oxygen-demanding constituents into receiving water bodies. Regulatory agencies in North America such as the U.S. EPA, Environment Canada and Provincial Ministries of Environment as well as the European Environment Agency (EEA) are directing efforts at outlining standards to limit maximum concentrations of oxygen-demanding compounds, especially concentrations of BOD and COD, being discharged directly or indirectly into water bodies (CEC, 1991; US EPA, 2004). Table 2.4 describes the standard levels and concentration limits of organic constituents to be discharged into water bodies as recommended by different worldwide agencies, including Environment Canada, the US EPA, the Council of the European Communities (CEC) among others.

Table 2.4. Comparison of different standards for slaughterhouse wastewater discharge.

Parameter	World Bank Standards[1]	EU Standards[2]	US Standards[3]	Canadian Standards[4]	Ontario Standards[5]	British Columbia Standards[6]
BOD_5 (mg/L)	50	25	26	Freshwater lakes, slow-flowing streams: 5. Rivers, streams and estuaries: 20. Shoreline 30.	25	45
COD (mg/L)	250	125	n/a	n/a	n/a	n/a
TSS (mg/L)	50	35	30	Freshwater lakes, slow-flowing streams: 5. Rivers, streams and estuaries: 20. Shoreline 30.	25	60
TN (mg/L)	10	10	8	1	1.25	n/a

[1] World Bank Group 2007; [2] CEC 1991; [3] US EPA 2004; [4] Environment Canada 2000; [5] ECO 2010; [6] BC MOE 2010.

Although, it can be seen that Canadian standards are very strict in comparison with other international regulations, such as the Council of the European Communities and the US EPA, Canada does not have a specific regulation for the meat and poultry processing industry. Nevertheless, some provinces, such as British Columbia, have been trying to develop a set of guidelines to specifically address MPP effluents by creating a code of practices that has been incorporated into the provincial Environmental Management Act, brought into force in 2004 (BC MOE, 2010). Moreover, the US EPA has been incorporating an integrated approach for the regulation of the MPP, where industry and regulatory sectors are working together in order to achieve a common goal of reducing the threats caused by the hazardous and high strength wastewaters produced in slaughterhouses. This approach includes different concepts, such as the Best Practicable Control Technology Available (BPT), Best Conventional Pollutant Control Technology (BCT), Best Available Technology Economically Achievable (BAT), New Source Performance Standards (NSPS), and Pre-treatment Standards for Existing Sources (PSES), for the better understanding of the procedures and regulations to follow under any situation; and thus, efficiency and cost-reduction without affecting quality.

Table 2.5 lists all methods for the analysis of different parameters of the slaughterhouse wastewater specified in the Ontario regulations (OMOE, 1996), including COD, BOD_5, total solids (TS), total Kjeldahl nitrogen (TKN), ammonia and ammonium nitrogen, nitrite and nitrate nitrogen, total phosphorus (TP), total potassium (TK), total sodium, pH, the 11 metals specified in the Ontario regulations (OMOE, 1996), and fat oil and grease (FOG).

Table 2.5. Methods used for analyzing various slaughterhouse wastewater parameters.

(Adapted from Wu and Mittal, 2011).

Method number	Equivalent APHA number	Parameters
MOE-E3091	3114	Arsenic, selenium
MOE-E3181	3030F	Calcium, chromium, cobalt, copper, lead, molybdenum, nickel, zinc
MOE-E3182	5010B	BOD_5
MOE-E3188	2540B	Total solids
MOE-E3218	2510B	Electrical conductivity, pH
MOE-E3246	5220	COD
MOE-E3301	3112B	Mercury
MOE-E3217	3111B	Calcium, magnesium, sodium, potassium
MOE-E3366	4500	Ammonia nitrogen, nitrite nitrogen, nitrite, nitrate nitrogen, phosphorus
MOE-E3368	$4500N_{org}$ D	Total Kjeldahl nitrogen, total phosphorus
MOE*	5520D	Fats, oils and greases

* No method number assigned to this method; MOE (Ministry of Environment); APHA (American Public Health Association); Unit for all except EC and pH is mg/L.

2.2.3. Environmental impacts

The commercialization of animal products for consumption leads without doubt to the production of high waste volumes. The environment is able to handle certain amounts of pollutants through several natural degradation processes. Nevertheless, as the concentration of waste increases, nature's mechanisms come to be overburdened and contamination problems commence. Therefore, new treatment methods have to be developed for a more efficient management of waste products.

In the slaughtering process, animals are reared, fattened, and transported. After processing, the meat is stored before it is transported to retail outlets; these activities produce manure. Storage and transport activities, where cooling facilities are needed, require large amounts of energy sources. Hides produced at slaughterhouses must be stored. To prevent spoilage, they should be pickled and preservatives are added. The methods used to process hides will determine the durability of the produced leather. The production of more durable leather leads to smaller quantities of leather waste. Chrome-tanned leather and leather products contain about 2–3% of dry weight chromium (Verheijen et al., 1996). Exhausted leather products, such as shoes and jackets, are frequently dumped at municipal dumping sites. Before its collection and transportation to a processing plant, milk is

produced and stored at the farm. This requires energy and leads to spoilage of milk and production of wastewater by cleaning activities. The most important environmental impact of the animal processing industry results from the discharge of wastewater. Most processes in slaughterhouses require the use of water, which produce wastewater. The strength and composition of pollutants in the wastewater evidently depend on the nature of the processes involved (Verheijen et al., 1996).

Biodegradable organic compounds (BOCs) from slaughterhouse activities have the greatest environmental impact (Masse and Masse, 2000b). Parameters used to determine BOCs are BOD, COD, and TSS. The BOD and COD are overall parameters that give an indication of the concentration of organic compounds in wastewater. The concentration of suspended solids represents the amount of insoluble organic and inorganic particles in the wastewater (Verheijen et al., 1996; Rajakumar et al., 2011).

On February 26, 2004, the EPA established new wastewater discharge limits (Table 2.6) for the meat and poultry products (MPP) industry, which also set effluent limits for poultry processors for the first time that causes a reduction in discharges of conventional pollutants, ammonia, and nitrogen to rivers, lakes, and streams (US EPA, 2004).

Table 2.6. US EPA effluent limitations for the meat and poultry products.

(Adapted from US EPA, 2004).

Regulated Parameter	Maximum Daily (mg/L)	Maximum Monthly (mg/L)
BOD_5	26	16
TSS	30	20
NH_3-N	8	4
TN	147–194	103–134

The discharge of raw slaughterhouse wastewater to water bodies can affect the quality of water in three main ways as follows:

1. The discharge of BOCs may cause a strong reduction of DO, which in turn may lead to reduced levels of activity or even death of aquatic life (Quinn and McFarlane, 1989; Sangodoyin and Agbawhe, 1992; Verheijen et al., 1996; Masse and Masse, 2000b; Torkian et al., 2003).

2. Macronutrients (N and P) may cause eutrophication of the receiving water bodies; while phosphates (PO42–) are the primary source of eutrophication; nitrogenous wastes contribute significantly to this water pollution problem. These nutrients cause an excessive algae growth and subsequent dying off. The mineralization of these algae may lead to the death of aquatic life because of oxygen depletion (Masse and Masse, 2000b; Belsky et al., 1999).
3. Finally, slaughterhouse wastewater effluents may contain compounds, such as chromium and unionized ammonia, which are directly toxic to aquatic life, as well as tannin, which is an astringent, bitter plant polyphenolic compound (Figure 2.2) that binds to and precipitates proteins and various other organic compounds including amino acids and alkaloids (Verheijen et al., 1996).

On the other hand, several studies show the impact of wastewater effluents loaded with high amounts of organic constituents on recipient water bodies. For example, the Ikpoba River in Nigeria is an example of water quality decrease. The river has being affected by high coliform concentrations stemming from discharged slaughterhouse wastewater. As described by Benka-Coker and Ojior (1995), the pathogenic bacteria concentration, including species such as *Escherichia coli*, *Salmonella*, *Shigella*, *Klebsiella*, *Streptococcus* and *Staphylococcus*, was increased from 104 to 107 CFU/100mL due to an untreated slaughterhouse effluent being discharged in upstream. The concentrations of TSS, BOD, nitrates, and phosphates were increased leading to a reduction of the concentration of DO from 7.2 to 2.4 mg/L. Therefore, the water quality of the receiving water was severely affected by not having a proper treatment technology for the reduction of the organic content from the slaughterhouse plant.

Likewise, the Bogota River flowing through Bogota, the capital city of Colombia, receives approximately 93,853 tonnes of total suspended solids and 75,016 tonnes of BOD_5 on an annual basis (Kingsley, 2011). Different sources, including slaughterhouses, upstream municipalities, horticultural facilities and coal yards, are responsible for the production of this high-strength wastewater. As a result, the Bogota River has several sections in which aquatic life no longer exists along with a putrefied odour derived from the abundant hydrogen sulphide in the river produced by the anaerobic biodegradation processes.

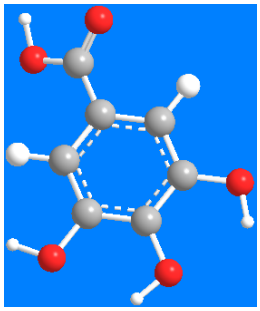
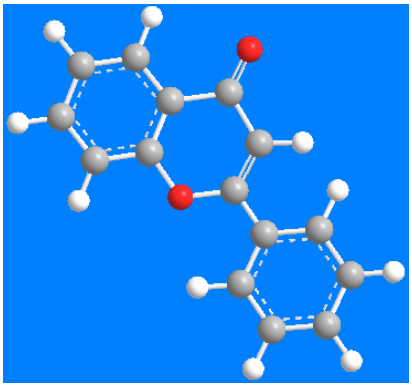
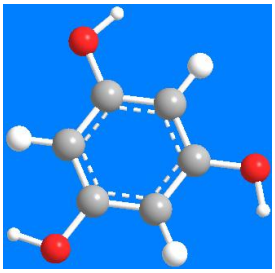
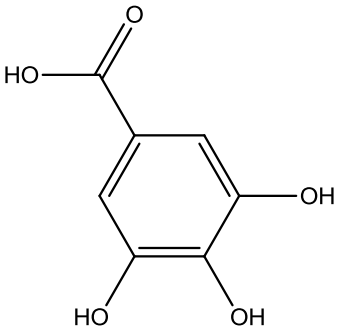
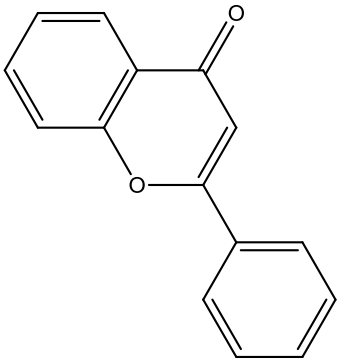
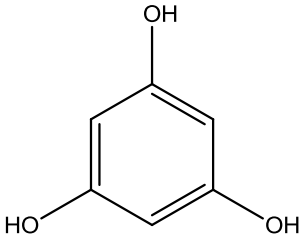
3D Model			
Structure			
Base Unit	Gallic acid	Flavone	Phloroglucinol
Class/Polymer	Hydrolyzable tannins	Non-Hydrolyzable tannins	Phlorotannins
Sources	Plants	Plants	Brown algae

Figure 2.2. Chemical structures for different classes of tannins.

2.2.4. Health effects

The Environmental Health and Safety (EHS) guidelines (Table 2.7) for meat processing, according to the World Bank Group include information relevant to meat processing, focusing on bovine and porcine slaughtering and processing from reception of the animals until the carcasses are ready for sale or further processing (World Bank Group, 2007). These guidelines are achievable under normal operating conditions in appropriately designed and operated facilities through the application of pollution prevention and control techniques.

Table 2.7. Effluent levels for meat processing.

(Adapted from World Bank Group, 2007).

Pollutants	**Guidelines Value**
pH	6–9
BOD (mg/L)	50
COD (mg/L)	250
TN (mg/L)	10
Oil and Grease (mg/L)	10
TSS (mg/L)	50
Temperature Increase (mg/L)	< 3**
Total Coliform Bacteria (MPN*/100ml)	400
Active Ingredients/Antibiotics	To be determined on a case specific basis

* MPN: Most Probable Number;
** At the edge of a scientifically established mixing zone that takes into account ambient water quality, receiving water use, potential receptors, and assimilative capacity.

Table 2.8 shows the standard levels recommended for slaughterhouse wastewater discharge in Canada (Environment Canada, 2000). These levels should be achieved without dilution for at least 95% of the plant or unit operation time. They are applicable to direct discharges of treated effluents to surface water for general use.

The impact of slaughterhouse wastewater on the soil and groundwater is characterized by pollution via nitrate and chloric anions, and many pathogenic microorganisms, which persist in the soil and reproduce continuously. Pathogenic microorganisms from cattle wastes can be also transmitted to humans who are exposed to the water body, making those areas non-suitable for drinking or irrigation purposes (Sangodoyin and Agbawhe, 1992; Benka-Coker and Ojior, 1995; Fang, 2000).

People from developing countries in South America and Africa have experienced serious gastrointestinal diseases, bloody diarrhoea, liver malfunctions, and in some cases, death associated with the presence of viruses, protozoa, helminthic eggs and bacteria in slaughterhouse wastewaters due to the poor management of the slaughterhouse wastewater (Prando and Gambogi, 2009; Krishna et al., 2009; Feng et al., 2009). In short, slaughterhouse wastewater must be treated efficiently before discharge into water bodies in order to avoid environmental pollution and human health effects (Belsky et al., 1999; Salminen and Rintala, 2002). On the other hand, wastewater workers in Cincinnati, Ohio; Anchorage, Alaska; and Ontario, Canada; have contracted *hepatitis A*. The Ontario workers worked in a primary purging station, grit chambers, and maintenance on sewer cleaning machines (Brown, 1997).

Table 2.8. Recommendations for wastewater discharges from federal facilities.

(Adapted from Environment Canada, 2000).

Parameters	**Water Bodies of Disposal**	**Disposal Recommendation**
BOD (mg/L)	Freshwater lakes, slow-flowing streams	5
	Rivers, streams and estuaries	20
	Shoreline	30
Fecal Coliforms (MPN*/100mL)		100
Total Coliform Count (MPN*/100mL)		1000
TSS (mg/L)	Freshwater lakes, slow-flowing streams	5
	Rivers, streams and estuaries	20
	Shoreline	30
Reactive Chlorine (mg/L)		0.01*
pH		6–9
Phenols (mg/L)		0.02
Oils and Grease (mg/L)		5
Temperature (°C)		>= 1
Ammonia (mg/L)		1
Nitrates (mg/L)		1
Phosphorus (mg/L)		1
Sulphurs (mg/L)		0.5
Chromium (mg/L)		0.05

* MPN: Most Probable Number or current detection limit.

2.3. Slaughterhouse wastewater treatment technologies

In natural water, there are two main routes for destroying toxic compounds, photodegradation, and biodegradation. Photodegradation is an important mechanism for degrading aromatic hydrocarbons, chlorinated aromatic hydrocarbons, chlorinated phenols, and many pesticides by direct or indirect photolysis, where a photosensitizer absorbs light and transfers the energy to pollutants. Biodegradation refers to the elimination of the pollutant by the metabolic activity of living organisms, usually microorganisms particularly bacteria and fungi that live in natural water and soil (Oller et al., 2011).

SSWW treatment technologies are similar to those used in municipal wastewater systems and may include primary, secondary, and even tertiary treatment for some cases (Wang et al., 2010). Physical, chemical, and biological treatment systems can be used in slaughterhouse wastewater decontamination. Each system has unique treatment advantages and disadvantages (Rajakumar et al., 2011). The feasibility of using many individual or combined reactor types to treat SSWW biologically has been examined in the past. Difficulties relating to fats and particulates have been mainly solved in the digestion processes (Debik and Coskun, 2009)

Physical processes are widely used in water and wastewater treatment plants. These physical techniques are based on the separation of one or more compounds from the waste stream. Because of the separation, the pollutant is transferred from one phase to another. Therefore, further treatment is required for the degradation of the contaminants in the second phase. Physical methods are employed mainly to separate large settleable and floating matter, clarify turbid solutions, recover, and recycle valuable substances utilized in the main processes and in separating inorganic materials. The conventional and advanced physical techniques include filtration, adsorption, gas stripping, and others.

Land application of slaughterhouse wastewater by spray irrigation has been used in the USA (Bull et al., 1982). Presently, in Ontario, land application of wastewater generated from slaughterhouse falls under the Environmental Protection Act (OMOE, 1996) and the determining factors for suitability are the same factors used for sewage, and pulp and paper biosolids (Wu and Mittal, 2011). Simplicity and low cost are its main advantages. Disadvantages include probable surface and ground water contamination, odours, production of greenhouse gases, and soil pore

obstruction from fat loads. Application on constructed wetlands could be also used as a polishing treatment for biologically treated wastewater (Johns, 1995). The land application, however, is not convenient at low temperatures (Masse and Masse, 2000b).

Grit chambers, screens, settling tanks, and dissolved air flotation (DAF) units are widely used for the removal of TSS, colloidal, and fats from slaughterhouse wastewater. In DAF units, aeration from the bottom of the tank move light solids, fat and grease to the surface where scum is periodically skimmed off.

Camin (1970) surveyed wastewater treatment in over 200 meatpacking plants in the USA and concluded that air flotation was the least efficient treatment in terms of dollars per weight of BOD removed in comparison to aerobic and anaerobic systems. Blood coagulants like aluminum sulphate and ferric chloride or flocculants like polymers are sometimes added to the wastewater in the DAF unit to increase protein flocculation and precipitation as well as fat flotation.

Chemical DAF units can reach COD reductions of between 32 and 90%, and are able to remove large amounts of nutrients. However, operational problems like the production of large volumes of rotten sludge that require special handling and further treatment have been reported (Johns, 1995).

Secondary treatment is aimed at reducing BOD concentration by removing the soluble organic compounds in either solution or suspension, which remain after primary treatment (Tchobanoglous et al., 2003). Biological treatment may include different combinations of various processes, including anaerobic, aerobic and facultative lagoons, activated sludge, and trickling filters among others (US EPA, 2004). These combined processes are capable of obtaining organic matter removal up to 90–95% at typical retention times of approximately 20 days (Tchobanoglous et al., 2003; Del Pozo and Diez, 2005; Wang, 2005).

Biological treatment is often the most applied process in slaughterhouse plants as secondary treatment, comprised of aerobic and anaerobic digestion that are used alone or combined depending on the characteristics of the wastewater being treated (Baruth, 2005).

Nevertheless, anaerobic digestion is the preferred biological treatment that is applied in slaughterhouse wastewater treatment due to its effectiveness in treating high-strength wastewater (Verheijen et al., 1996; Tchobanoglous et al., 2003; US EPA, 2004; Cao, 2009; Cao and Mehrvar, 2011). Table 2.9 shows a summary of the current SSWW treatment technologies that have been successfully applied to deal with the environmental impacts and health effects caused by these high-strength wastewaters.

Table 2.9. Summary of current technologies used in MPP facilities for the treatment of the slaughterhouse wastewater.

(Adapted from US-EPA, 2002; Mittal, 2006; Cao, 2009).

Category	**Regulatory Level**	**Technology Description**
Simple abattoir	BPT[1]	Equalization, DAF[2], Secondary Biological Treatment with nitrification
Complex abattoir	BPT	Equalization, DAF, Secondary Biological Treatment with nitrification and denitrification
Low-processing packaging	BAT[3]; NSPS[4]	Equalization, DAF, Secondary Biological Treatment with nitrification and denitrification
High-processing packaging	BAT; NSPS	Equalization, DAF, Secondary Biological Treatment with nitrification
Meat cutter	BPT	Equalization, DAF, Secondary Biological Treatment with nitrification
Sausage and luncheon meats processor	BPT	Equalization, DAF, Secondary Biological Treatment with nitrification and denitrification
Ham processor	BAT; NSPS	Equalization, DAF, Secondary Biological Treatment with nitrification and denitrification
Canned meat processor	BAT; NSPS	Equalization, DAF, Secondary Biological Treatment with nitrification
Renderer	BPT; BCT[5]; BAT; NSPS	Equalization, DAF, Secondary Biological Treatment with nitrification
Poultry first processing (facilities which slaughter up to 5000 tonnes/year)	BPT; BCT	Equalization, DAF, Secondary Biological Treatment with nitrification and denitrification
Poultry further processing (facilities which produce up to 3.5 tonnes/year or finished product)	BAT; NSPS	Equalization, DAF, Secondary Biological Treatment with nitrification and denitrification

[1] BPT: Best practicable control technology currently available; [2] DAF: Dissolved Air Flotation; [3] BAT: Best available technology economically achievable; [4] NSPS: New source performance standards; [5] BCT: Best control technology for conventional pollutants.

2.3.1. Anaerobic biological treatment

During anaerobic digestion, organics are degraded by a diversity of bacteria into methane in the absence of oxygen. Anaerobic systems have several advantages such as high efficiency in reducing COD in soluble and insoluble form; a low sludge production of only 5 to 20% of that generated by aerobic systems (Masse and Masse, 2000b); the recovery of usable energy in the form of methane; no aeration energy requirement; and no chemical handling. In addition, the biomass can remain unfed for a long period without deteriorating.

Microorganisms are the main parameter in terms of organic matter digestion in biological treatment of water and wastewater. During anaerobic digestion, microbes convert organic compounds into oxidized substances, new cells, energy for their life processes, and some gaseous products, such as methane and carbon dioxide (Reynolds and Richards, 1996) as shown in Reaction (2.1).

$$Organics + Dissolved\ oxygen\ (DO) \xrightarrow{\substack{Anaerobic \\ microbes}} Energy + New\ cells + CH_4 + CO_2 + Others \quad (2.1)$$

The advantages of anaerobic treatment outweigh the advantages of aerobic treatment when treating influents in higher concentrations, and generally, anaerobic treatment requires less energy with potential bioenergy and nutrient recovery. Although anaerobic treatment possesses great advantages, it hardly produces effluents that comply with usual discharge standards established by environmental agencies. In most applications, despite the high efficiency of the anaerobic process, the complete stabilization of the organic matter is impossible anaerobically due to the high organic strength of the wastewater. Thus, the effluents from anaerobic reactors usually need a post-treatment step, in which the removal of organic matter and other constituents, slightly affected by the anaerobic treatment such as nutrients (N/P) and pathogenic organisms, is completed (Chernicharo, 2006). The final effluent produced by the anaerobic treatment usually contains solubilised organic matter, suitable for aerobic treatment, indicating the potential of using anaerobic–aerobic systems (Gray, 2005), where subsequent post-treatment using aerobic treatment is required to meet the effluent discharge standard.

2.3.2. Aerobic biological treatment

In aerobic digestion, microorganisms degrade organics in the presence of oxygen. One disadvantage of aerobic systems is the generation of large quantities of biological sludge that must be treated before disposal (Bull et al., 1982). High BOD removals have been reported, but effluent TSS concentrations are often elevated due to poor sludge settleability (Johns, 1995). In addition, oxygen requirements and treatment time increase suddenly with wastewater strength. Aerobic treatment could be used for final decontamination and nutrient removal following physicochemical or anaerobic techniques (Van Lier et al., 2001; Chernicharo, 2006). Compared to anaerobic systems, aerobic systems achieve higher removal of soluble biodegradable organic matter and the produced biomass is generally well flocculated, resulting in a lower concentration of suspended solids in the effluent (Grady et al., 1999). As a result, the effluent quality from aerobic systems is generally higher than that of anaerobic systems.

2.3.3. Combined anaerobic-aerobic biological treatment

Both anaerobic and aerobic systems are capable of achieving high organic removal efficiencies as shown in Table 2.10. In general, aerobic systems are suitable for the treatment of low strength wastewaters (biodegradable COD concentrations less than 1000 mg/L) while anaerobic systems are suitable for the treatment of high strength wastewaters (biodegradable COD concentrations over 4,000 mg/L).

Table 2.10. Comparison of anaerobic and aerobic wastewater treatment technologies.

(Adapted from Yeoh, 1995; Grady et al., 1999; Chan et al., 2009).

Feature	Aerobic	Anaerobic
Organic removal efficiency	High	High
Effluent quality (aesthetics)	Excellent	Moderate to poor
Organic loading rate	Moderate	High
Sludge waste production	High	Low
Nutrient requirement	High	Low
Alkalinity requirement	Low	High for certain industrial waste
Energy requirement	High	Low to moderate
Temperature sensitivity	Low	High
Start-up time	2–4 weeks	2–4 months
Odour	Less opportunity for odours	Potential odour problems
Bioenergy and nutrient recovery	No	Yes
Mode of treatment	Total (depending on feedstock characteristics)	Essentially pre-treatment

Aggelis et al. (2001) found that neither anaerobic nor aerobic processes could be employed alone for efficient treatment. When treating high organic strength industrial wastewaters, the aerobic or anaerobic treatment alone does not produce effluents that comply with the effluent discharge limit. The use of combined anaerobic-aerobic processes can also lead to a reduction in operating costs when compared with aerobic treatment alone (Vera et al., 1999), while simultaneously resulting in high organic matter removal efficiency and smaller amounts of aerobic sludge without pH correction. Benefits of the combined anaerobic–aerobic processes include a great potential for resource recovery as anaerobic pre-treatment removes most of the organic pollutants and converts them into biogas and a high overall treatment efficiency as aerobic post-treatment polishes the anaerobic effluent and results in very high overall treatment efficiency (Frostell, 1983; Cervantes et al., 2006).

Combined anaerobic-aerobic systems have been also found to perform well for several processes such as biodegradation of chlorinated aromatic hydrocarbons including anaerobic de-chlorination and aerobic ring cleavage (Supaka et al., 2004); sequential nitrogen removal including aerobic nitrification and anaerobic denitrification (Liu et al., 2008); and anaerobic reduction of Fe (III) and micro-acrophilic oxidation of Fe (II) with production of fine particles of iron hydroxide for adsorption of organic acids, phenols ammonium, cyanide, radionuclides, and heavy metals (Wang, 2005). Combined anaerobic-aerobic systems using high-rate bioreactors, such as upflow anaerobic sludge blankets (UASB), filter bioreactors, fluidized bed reactors and membrane bioreactors, are adopted in order to provide a treatment process that is both technologically and economically viable with the dual goals of resource recovery and compliance with current legislation for effluent discharge. A more intensive form of biodegradation can be also achieved by integrating anaerobic and aerobic zones within a single bioreactor. Essentially, there are four types of integrated anaerobic-aerobic bioreactors, which are explained as follows:

1. Integrated bioreactors with physical separation of anaerobic-aerobic zone;
2. Integrated bioreactors without physical separation of anaerobic-aerobic zone;
3. Sequencing batch reactors (SBR) based on temporal separation of the anaerobic and the aerobic phase; and
4. Combined anaerobic–aerobic systems based on the principle of limited oxygen diffusion in microbial biofilms.

In recent years, substantial attention has been paid to compact high-rate bioreactors for wastewater treatment to meet the strict constraints with respect to space, odour, and biosolids production (Chan et al., 2009). Thus, integrated bioreactors, which combine aerobic and anaerobic processes in a single reactor, have been seen as a viable alternative. This combination is capable of enhancing the overall degradation efficiency (Tartakovsky et al., 2005). The integrated bioreactors are cost-effective, efficient, and have smaller footprints as compared to other anaerobic–aerobic systems. Nonetheless, the design, operation, and process development of integrated anaerobic–aerobic bioreactors are still emerging (Chan et al., 2009).

2.3.4. Biological modeling

Theoretically, the growth of microorganisms is represented by five stages, including the lag phase, exponential growth phase, deceleration phase, stationary phase, and death phase (Reynolds and Richards, 1996). Figure 2.3 shows a typical microbial growth based on biomass concentration.

Organic matter in slaughterhouse wastewater can be represented by TOC and TN due to the multiple organic compounds in the wastewater. Table 2.11 shows the main parameters of the biological treatment together with their calculation methods.

Table 2.11. Main parameters for biological treatment.

(Adapted from Del Pozo and Diez, 2005).

Parameter	Calculation	Definition
OLR (mgTOC/L.h)	$TOC_o(F)/Vr$	Organic loading rate
rTOC (mgTOC/L.h)	$F(TOC_o - TOC)/Vr$	Overall TOC removal rate
rTOCmet (mgTOC/L.h)	$G(X_{CH4})/(0.38Vr)$	Methanogenic TOC removal rate
$rTOC_{Anox}$ (mgTOC/L.h)	$2.9G(X_{N2})/(0.87Vr)$	TOC removal rate by denitrification
$rTOC_{Ae}$ (mgTOC/L.h)	rTOC – rTOCanox – rTOCmet	Aerobic TOC removal rate
%TOC	$100(TOC_o - TOC)/Vr$	Overall TOC removal efficiency
NLR (mgTN/L.h)	$TN_o(F)//Vr$	Nitrogen loading rate
NLR_{Ae} (mgTN/L.h)	$TN_o(F)//V_{Ae}^*$	Local nitrogen load in the aerobic zone
rNdn (mgN/L.h)	$G(X_{N2})/(0.87Vr)$	Denitrification rate
rNn (mgN/L.h)	F(NO-N)$/Vr$ + rNdn	Nitrification rate
%TN	$100(TN_o - (NH\text{-}N + NO\text{-}N))/TN_o$	Overall nitrogen removal efficiency
%Nn	$100(TN_o - NH\text{-}N)/TN_o$	Nitrification efficiency

Notes: Ae, aerobic; met, methanogenic; Ana, anaerobic; Anox, anoxic; n, nitrification; dn, denitrification; g, growth; F, feed; G, biogas production (L/h); X_{CH4}, methane molar fraction in biogas; X_{N2}, nitrogen molar fraction in biogas. $^*V_{Ae}$ = 1/5, 2/5 or 3/5Vr.

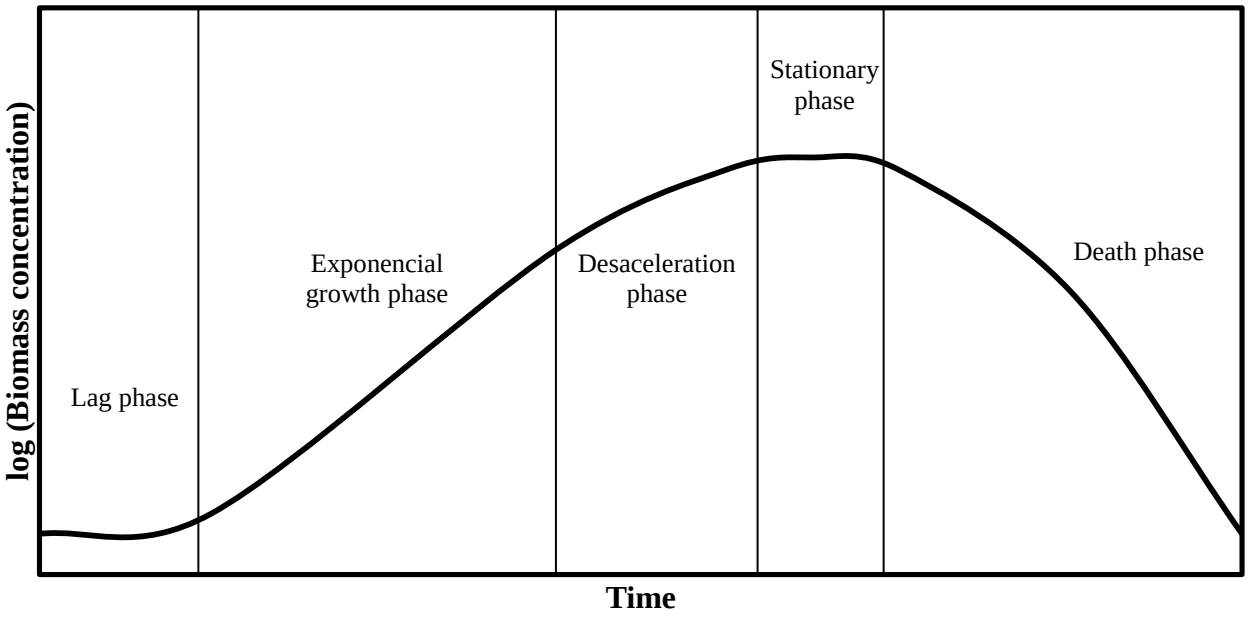


Figure 2.3. A typical curve for the microbial growth.

The loading rates have been expressed on a volumetric basis (mg/L.h) instead of an attachment surface basis because there is an important bed of suspended biomass that can stand at the bottom of the reactors, where V_r is the effective volume. Removal of organic matter from methanogenic and anoxic processes has to be calculated from biogas production and concentration of methane and nitrogen, respectively.

Overall nitrogen removal efficiency (%TN) should be calculated from the difference between the feed TN and the nitrogen as ammonia (NH-N) or nitrite and nitrate (NO-N) in the effluent. The nitrification efficiency ($\%N_n$) should be estimated from the TN removal where the nitrogen employed in biomass growth and the released amount in biomass lysis can be ignored.

In cases in which nutrient removal is required to meet the quality standards of the receiving water bodies, the use of anaerobic processes preceding a complementary aerobic treatment for biological nutrient removal should be analyzed. Anaerobic systems present good biodegradable organic matter removal, but not necessarily removal efficiency. This certainly causes a negative effect on biological treatment systems aiming at good nutrient removal. When the purpose of the treatment is also good nitrogen removal, the anaerobic reactor should be used to treat initially only a part of the influent raw sewage (possibly no more than 50–70%), and the remaining part (30–50%) should be directed to the complementary biological treatment, aiming at nitrification and denitrification, so that there is enough organic matter for the denitrification step. In this case, the great advantage in using the anaerobic reactor is to receive and stabilize the sludge generated in the complementary treatment, eliminating the need for an anaerobic sludge digester (Chernicharo, 2006).

Usually biological reactions are modeled by *Monod* (Edalatmanesh et al., 2008; Mohajerani et al., 2009; Cao, 2009; Cao and Mehrvar, 2011), *Haldane* (Edalatmanesh et al., 2008; Mohajerani et al., 2009), *two-step Haldane* (Edalatmanesh et al., 2008; Mohajerani et al., 2009), *Contois* (Mohajerani et al., 2009), and *Grau* (Mohajerani et al., 2009). The *Monod* equation has been found as an acceptable and powerful mathematical expression fitted to experimental data described as follows (Edalatmanesh et al., 2008; Mohajerani et al., 2009):

$$X = X_{max} \frac{TOC}{K_{TOC}+TOC} \tag{2.2}$$

Where X and X_{max} are the specific and maximum specific growth rates of microorganisms, K_{TOC} is the half-saturation constant, and TOC is the total organic carbon concentration standing for any limiting organic source. In case of K_{TOC} << TOC, applicable to no inhibition, the *Monod* equation can be simplified as follows (Edalatmanesh et al., 2008; Mohajerani et al., 2009):

$$X = \frac{1}{VSS}\frac{dVSS}{dt} = X_{max}\frac{TOC}{K_{TOC}+TOC} \cong X_{max} \quad (2.3)$$

A cell yield coefficient can be defined based on the TOC consumption and volatile suspended solids (VSS) production during aerobic biochemical degradation and it can be defined as follows (Edalatmanesh et al., 2008; Mohajerani et al., 2009):

$$\Upsilon_{VSS/TOC} = \frac{VSS-VSS_o}{VSS_o-TOC} \quad (2.4)$$

Where VSS_o and VSS are initial and final concentrations of volatile suspended solids in the bioreactor, and $TOC_o - TOC$ is the organic consumption during the biological treatment. Equation (2.4) can be also employed based on the utilization of the biodegradable TOC fraction (Mohajerani et al., 2009). The *Monod* expression can be employed for modeling as shown in Equation (2.5). Consequently, Equation (2.7) can be obtained by considering K_{TOC} << TOC.

$$-\frac{1}{VSS}\frac{dTOC}{dt} = \frac{X}{\Upsilon_{VSS/TOC}} = \frac{X_{max}(TOC)}{K_{TOC}+TOC}\left[\frac{TOC_o-TOC}{VSS-VSS_o}\right] \quad (2.5)$$

$$-\frac{dTOC}{dt} = \frac{X_{max}(TOC)(TOC_o-TOC)(VSS)}{(K_{TOC}+TOC)(VSS-VSS_o)} = \frac{X_{max}(VSS)(TOC_o-TOC)}{K_{TOC}(VSS-VSS_o)} \quad (2.6)$$

$$\frac{dTOC}{dt} = \frac{X_{max}(VSS)(TOC_o)}{K_{TOC}(VSS-VSS_o)} - \frac{X_{max}(VSS)(TOC)}{K_{TOC}(VSS-VSS_o)} \quad (2.7)$$

Finally, assuming two variables *a* and *b*, as shown in Equation (2.8), the final simplified Equation (2.9) can be obtained; where, a plot of the left side of the final equation versus *t* should give a straight line to find the parameters of interest.

$$a = \frac{X_{max}(VSS)(TOC_o)}{K_{TOC}(VSS-VSS_o)}, and\ b = \frac{X_{max}(VSS)}{K_{TOC}(VSS-VSS_o)} \quad (2.8)$$

$$\frac{\ln[a-b(TOC)]}{\ln[a-b(TOC_o)]} = bt \quad (2.9)$$

Kennedy and Barriault (2007) developed a first order model to describe the substrate concentration driving force within different compartments of an ABR. This model has three major assumptions as follows:

1. The soluble component in an *n*-compartment ABR as whole is the representative of *n*-continuous stirred tank reactors (CSTRs) in series;
2. The system would act as one large CSTR where the recycle rate is high compared to the influent flow; and
3. The methane production is the rate-limiting step.

The first order rate constant could be calculated from operational treatment data knowing the substrate concentrations and biomass in each compartment. The mass balance in the first compartment and subsequent *i* compartments of an *n*-compartment ABR are presented in Equations (2.10) and (2.11), respectively.

Under steady-state conditions, dS_1/dt and dS_i/dt = 0, then Equations (2.10) and (2.11) are reduced to Equations (2.12) and (2.13), respectively, which are used to estimate the values of the first order rate coefficient of each compartment. In case of no recycle, r_r = 0; thus, Equations (2.12) and (2.13) can be reduced to Equation (2.14):

$$\frac{dS_1}{dt}V_1 = QS_o + r_rQS_f - (1+r_r)QS_1 - k_{C1}S_1X_1V_1 \quad (2.10)$$

$$\frac{dS_i}{dt}V_i = (1+r_r)QS_{i-1} - (1+r_r)QS_i - k_{Ci}S_iX_iV_i \quad (2.11)$$

$$S_1 = \frac{S_o+r_rS_f}{(1+r_r+k_{C1}X_1V_1/Q)} \quad (2.12)$$

$$S_i = \frac{S_{i-1}(1+r_r)}{(1+r_r+k_{Ci}X_iV_i/Q)} \quad (\text{for } i \geq 2) \quad (2.13)$$

$$S_i = \frac{S_{i-1}}{(1+k_{Ci}X_iV_i/Q)} \qquad \text{(for } i \geq 1\text{)} \tag{2.14}$$

where,

S_o = concentration of the substrate in the influent (mg/L);

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

S_{i-1} = concentration of the substrate in compartment *i-1* of the ABR (mg/L);

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

S_1 = concentration of the substrate in compartment 1 of the ABR (mg/L);

r_r = recycle rate in the ABR, which is a percent of the flow rate of the influent (%);

k_{Ci} = first order rate coefficient of substrate in compartment *i* of the ABR;

k_{C1} = first order rate coefficient of substrate in compartment 1 of the ABR;

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

X_1 = biomass concentration of substrate in compartment 1 of the ABR (mg/L);

V_i = volume of the compartment *i* of the ABR (L);

V_1 = volume of the compartment 1 of the ABR (L); and

Q = flow rate of influent (L/h).

2.3.5. Nitrification and denitrification

Bacteria remove nitrogen from wastewater by two-step biological processes, nitrification followed by denitrification. Technically, it is a three-step process, since ammonification precedes nitrification and denitrification. During ammonification, the majority of the nitrogen contained in raw sewage is converted from organic-nitrogen to ammonia (NH_3) through a process called hydrolysis; in common situations, more ammonium (NH_4^+) than ammonia is created during ammonification, and the actual ratio is influenced by pH and temperature.

The biological conversion of ammonium (NH_4^+) to nitrate nitrogen (NO_3^-) is called nitrification, which is a two-step process. First, *Nitrosomonas* bacteria convert ammonia (NH_3) and ammonium (NH_4^+) into nitrite (NO_2^-). Next, *Nitrobacter* bacteria finish the conversion of nitrite (NO_2^-) to nitrate (NO_3^-). These bacteria, known as *nitrifiers*, are commonly *aerobes*, meaning they must have free dissolved oxygen (DO) to perform their work (Zhang et al., 2009). Nitrification occurs only under aerobic conditions at dissolved oxygen levels of 1.0 mg/L or more. At dissolved oxygen concentrations of less than 0.5 mg/L, the growth rate is minimal. The reactions are generally coupled

and go rapidly to the nitrate (NO_3^-) form; therefore, nitrite (NO_2^-) levels at any given time are usually low (Ward, 1996). The following reactions describe the nitrification process:

$$2NH_4^+ + 3O_2 \rightarrow 4H^+ + 2H_2O + 2NO_2^- \quad (2.15)$$

$$2NO_2^- + O_2 \rightarrow 2NO_3^- \quad (2.16)$$

Although ammonium ions are used as an energy source by nitrifying bacteria, not all of the ammonium ions taken inside the bacterial cells are nitrified. Some of the ammonium ions are used as a nutrient source for nitrogen and are assimilated into new cellular material ($C_5H_7O_2N$). The growth of new cells in the activated sludge process is referred to as an increase in the mixed liquor volatile suspended solids (MLVSS) (Gerardi, 2002):

$$4CO_2 + HCO_3^- + NH_4^+ + 4H_2O \rightarrow C_5H_7O_2N + 5O_2 + 3H_2O \quad (2.17)$$

Carbon dioxide (CO_2) serves as the carbon source for the synthesis of cellular material, and is available to nitrifying bacteria as bicarbonate alkalinity. This alkalinity is produced when carbon dioxide dissolves in wastewater (Gerardi, 2002).

The biological reduction of nitrate (NO_3^-) to nitrogen gas (N_2) by facultative heterotrophic bacteria is called denitrification. Heterotrophic bacteria need a carbon source as food to live. Facultative bacteria can get their oxygen by taking dissolved oxygen out of the water or by taking it off nitrate molecules (Ward, 1996).

Denitrification occurs when oxygen levels are depleted and nitrate becomes the primary oxygen source for microorganisms. The process is performed under anoxic conditions, when the dissolved oxygen concentration is less than 0.5 mg/L, ideally less than 0.2 mg/L (Chen and Lin, 1993). When bacteria break apart nitrate (NO_3^-) to gain oxygen (O_2), the nitrate is reduced to nitrous oxide (N_2O), and in turn, to nitrogen gas (N_2). Nitrogen gas has low water solubility; therefore, it escapes into the atmosphere as gas bubbles (Zumft, 1997). Free nitrogen is the major component of air; thus, its release does not cause any environmental concern. The reaction pathway of the denitrification generally proceeds through some combination of the intermediates as shown below:

$$NO_3^- \rightarrow NO_2^- \rightarrow NO + N_2O \rightarrow N_2(g) \quad (2.18)$$

Moreover, the complete denitrification process can be expressed as a redox reaction as shown in Reaction (2.19), and generally speaking, the denitrification reaction can be described as shown in Reaction (2.20), where a carbon source (CH_3OH) is often required for denitrification to occur.

$$2NO_3^- + 10e^- + 12H^+ \rightarrow N_2 + 6H_2O \quad (2.19)$$

$$6NO_3^- + 5CH_3OH \rightarrow 3N_2 + 5CO_2 + 7H_2O + 6\,OH^- \quad (2.20)$$

Since denitrifying bacteria are facultative organisms, they can use either dissolved oxygen or nitrate as an oxygen source for metabolism and oxidation of organic matter. If dissolved oxygen and nitrate are present, bacteria will use the dissolved oxygen first (Zumft, 1997).

2.3.6. Advanced oxidation processes (AOPs)

The use of advanced oxidation processes (AOPs) can also become an interesting alternative for post-treatment of biologically treated effluents. In this context, conventional biological processes do not always provide satisfactory results, especially for industrial and high-concentrated wastewater since many of the organic substances produced by various industries are toxic or resistant to biological treatment (Steber and Wierich, 1986; Bowers et al., 1989; Adams et al., 1996; Pulgarín and Kiwi, 1996; García et al., 2001; Muñoz and Guieysee, 2006; Lapertot et al., 2006). Therefore, one feasible option for such biologically persistent wastewater is the use of advanced oxidation technologies based on chemical oxidation widely recognized as a highly efficient treatment alternative for recalcitrant wastewater.

AOPs degrade organic pollutants by forming hydroxyl radicals ($^{\bullet}OH$) (Balcioglu et al., 2001; Bhatkhande et al., 2002; Neyens and Baeyens, 2003; Gonze et al., 2003; Sarria et al., 2003; García-Montaño et al., 2006), which are highly reactive and non-selective (Gogate and Pandit, 2004a; Gogate and Pandit, 2004b; Pera-Titus et al., 2007; Devipriyas and Yesodharan, 2005; Pignatello et al., 2006; Comninellis et al., 2008; Shannon et al., 2008). This species can degrade organic matter rapidly in comparison with ordinary chemical oxidation processes that may take months and even years to accomplish this. The fast oxidation, in terms of seconds, of the organic matter by the $^{\bullet}OH$ species

allows the use of the term "advanced" (Bolton and Cotton, 2008) for this kind of process. AOPs include photochemical degradation processes, such as UV/H_2O_2, UV/O_3, and UV/O_3/H_2O_2, in which UV radiation plays a secondary role by initiating the photoreaction in the presence of an auxiliary oxidant to produce $^{\bullet}$OH radicals; photocatalytic processes, such as TiO_2/UV and photo-Fenton reactors, in which a catalyst plays a secondary role by absorbing UV radiation to produce $^{\bullet}$OH radicals; and chemical oxidation, such as O_3, O_3/H_2O_2 and H_2O_2/Fe^{2+} among others (Tchobanoglous et al., 2003; Oppenländer, 2003).

AOPs are also governed by the same principles as the common chemical processes associated with redox reactions, which involve the exchange of electrons between chemical species, leading to a change in the oxidation state of different compounds taking place in the process (Sawyer et al., 2002). In redox reactions, the compounds gaining electrons are known as oxidizing agents, while compounds losing electrons are known as reducing agents. Thus, $^{\bullet}$OH radicals, produced from AOPs, are strong oxidizing agents, which are highly reactive to organic matter.

As McMurray and Fay (2003) show, the exchange of electrons between an oxidant and a reducer is spearheaded by the difference in their standard electrode potential (E^o). $^{\bullet}$OH intermediates have one of the highest electrical oxidation potentials (EOP) (2.80V) among all typical chemical oxidizing agents used in water and wastewater treatment technologies as shown in Table 2.12 (Tarr, 2003; Asano et al., 2007; Black and Veatch, 2010).

Table 2.12. Standard electrode potential of selected oxidant species.

(Adapted from Tarr, 2003 and Barrera, 2011).

Oxidant	**EOP (V)**
Fluorine (F)	3.03
Hydroxyl radical ($^{\bullet}$OH)	***2.80***
Atomic oxygen (O)	2.42
Ozone (O_3)	2.07
Hydrogen peroxide (H_2O_2)	1.77
Permanganate ion (MnO_4^{2-})	1.67
Hypochlorous acid (HClO)	1.49
Chlorine (Cl)	1.36
Chlorine dioxide (ClO_2)	1.27
Bromine (Br)	1.09

Furthermore, hydroxyl radicals ($^{\bullet}OH$), which have a high oxidation potential, attack organic molecules by either abstracting or adding a hydrogen atom to double bonds, thus allowing their mineralization to non-toxic forms such carbon dioxide or water. Studies carried out by Sigge et al. (2002) demonstrated the feasibility of this process in further reducing the TOC contents of anaerobic effluents, when using ozone and ozone/hydrogen peroxide in combination with a granular activated carbon contacting column. In one study, colour and COD reductions ranged from 66 to 90% and from 27 to 55%, respectively (Chernicharo, 2006). In some cases, the mineralization of an organic compound cannot be reached, but the toxicity of the parent compound is reduced and eventually it can be treated by cheaper methods such as biological treatment (Tarr, 2003; Tchobanoglous et al., 2003).

Chemical oxidation for complete mineralization is generally expensive because the oxidation intermediates, formed during treatment, tend to be more and more resistant to their complete chemical degradation. Moreover, they all consume energy (e.g. UV radiation, ozone) and chemical reagents like catalysts and oxidizers, which increase with treatment time (Muñoz et al., 2005). Appropriate techniques must be combined to provide technically and economically feasible options.

In combined chemical and biological wastewater treatment, it is very important to keep in mind how the characteristics of each individual treatment, such as the chemical oxidant to be used (i.e. photo-Fenton or Fenton reagent, O_3/H_2O_2, UV/O_3, UV/H_2O_2, UV/TiO_2, etc.) can improve the destruction of a persistent contaminant (Liu et al., 2008; Comninellis et al., 2008; Klavarioti et al., 2009).

The rest of the aspects to be considered are also widely known: the chemical oxidation capacity (Jones et al., 1985; Lee and Carberry, 1992), its potential for forming toxic intermediates (Trgovcich et al., 1983; Bowers et al., 1989; Wang, 1992), a change in pollutant behaviour (Miller et al., 1988; Eckstein, 1994), the choice of biological agent, the comparison of different cultures (Lee and Carberry, 1992), the comparison of acclimated and non-acclimated cultures (Bowers et al., 1989; Hu and Yu, 1994), and the use of monospecific cultures and anaerobic cultures (Koyama et al., 1994; Adams et al., 1994). Measurement of the combined process efficiency depends on the purpose of the treatment, but normally requires the independent optimization of each chemical and biological step (Oller et al., 2011).

2.3.7. UV/H_2O_2 process

H_2O_2 and O_3 are chemical compounds that can be considered as auxiliary oxidants when coupled with UV radiation, usually under the UVC region of the electromagnetic spectrum between 200 to 280 nm as shown in Table 2.13 in order to produce $^{\bullet}OH$ species. The UV/H_2O_2 process, one of the most widely AOPs, is an effective technology for industrial wastewater treatment (Tabrizi and Mehrvar, 2004; Aye et al., 2004; Edalatmanesh et al., 2008; Mohajerani et al., 2009). The degradation and detoxification of pollutants in the UV/H_2O_2 process rely on highly reactive species, where $^{\bullet}OH$ are produced from the reaction of the H_2O_2 with the UV light (Glaze, 1987; Zhou and Smith, 2002; Edalatmanesh et al., 2008; Mohajerani et al., 2009).

The UV/H_2O_2 process uses ultraviolet radiation to cleave the O–O bond in hydrogen peroxide (H_2O_2) and generate hydroxyl radicals. The $^{\bullet}OH$ can be then scavenged by an organic compound to initiate a radical chain degradation of H_2O_2 in the series of reactions shown below (Clarke and Knowles, 1982; Glaze, 1987).

$$H_2O_2 \xrightarrow{hv} 2\ {}^{\bullet}OH \quad (2.21)$$

$$^{\bullet}OH + RH \rightarrow H_2O + R^{\bullet} \quad (2.22)$$

$$R^{\bullet} + H_2O_2 \rightarrow ROH + {}^{\bullet}OH \quad (2.23)$$

$$R^{\bullet} + O_2 \rightarrow ROO^{\bullet} \quad (2.24)$$

$$ROO^{\bullet} + RH \rightarrow ROOH + R^{\bullet} \quad (2.25)$$

Table 2.13. Electromagnetic spectrum of ultraviolet light.

Name	Abbreviation	Wavelength range (nm)	Energy per photon (eV)
Before UV spectrum; visible light	VIS	above 400	below 3.10
Ultraviolet A, long wave, or black light	UVA	400–315	3.10–3.94
Near	NUV	400–300	3.10–4.13
Ultraviolet B or medium wave	UVB	315–280	3.94–4.43
Middle	MUV	300–200	4.13–6.20
Ultraviolet C, short wave, or germicidal	UVC	280–100	4.43–12.4
Far	FUV	200–122	6.20–10.2
Vacuum	VUV	200–100	6.20–12.4
Low	LUV	100–88	12.4–14.1
Super	SUV	150–10	8.28–124
Extreme	EUV	121–10	10.2–124
Beyond UV range	X-rays	below 10	above 124

The $^{\bullet}OH$ produced in either way described above may attack organic molecules by abstracting a hydrogen atom from the molecule (Clarke and Knowles, 1982). Carey (1990) described a common pathway for the degradation of organics by the $^{\bullet}OH$. As seen in Reaction (2.21), 2 moles of $^{\bullet}OH$ are produced per quantum of radiation (*hv*) absorbed; however, there are other reactions to be considered such as the radical-radical recombination as shown in Reaction (2.26), which takes place when the H_2O_2 concentration is high during the oxidation process, which is responsible for the overall reduction of the efficiency of the process.

$$^{\bullet}OH + {}^{\bullet}OH \rightarrow H_2O_2 \tag{2.26}$$

A recombination may be avoided by finding the optimum H_2O_2 concentration inherent to the specific contaminant and system configuration (Oppenländer, 2003). The major photochemical and chemical reactions taking place in the UV/H_2O_2 process can be described as shown in Table 2.14.

Table 2.14. Common reaction mechanisms in UV/H_2O_2 processes.

Reaction No.	Reaction	Quantum Yield, ϕ (mol/E)	Reaction rate constant, k (1/M.s)	Reference
(2.27)	$H_2O_2 + h\nu \xrightarrow{\phi_1} 2\ ^{\bullet}OH$	0.500		Buxton et al. (1988)
(2.28)	$TOC + h\nu \xrightarrow{\phi_2} intermediates \rightarrow CO_2 + H_2O$	0.032		Barrera (2011)
		0.027		**This study**
(2.29)	$H_2O_2 + {}^{\bullet}OH \xrightarrow{k_1} HO_2^{\bullet} + H_2O$		$k_1 = 2.7\times10^7$	Christensen et al. (1982)
(2.30)	$^{\bullet}OH + {}^{\bullet}OH \xrightarrow{k_2} H_2O_2$		$k_2 = 5.0\times10^9$	Staehelin et al. (1984)
(2.31)	$2\ ^{\bullet}OH \xrightarrow{k_3} H_2O_2$		$k_3 = 6.0\times10^9$	Staehelin et al. (1984)
(2.32)	$^{\bullet}OH + HO_2^{\bullet} \xrightarrow{k_4} H_2O_2 + O_2$		$k_4 = 8.3\times10^5$	Bielski et al. (1985)
(2.33)	$2HO_2^{\bullet} \xrightarrow{k_5} H_2O_2 + O_2$		$k_5 = 1.5\times10^6$	Buxton et al. (1988)
(2.34)	$HO_2^{\bullet} + {}^{\bullet}OH \xrightarrow{k_6} H_2O + O_2$		$k_6 = 6.6\times10^9$	Buxton et al. (1988)
(2.35)	$H_2O_2 + HO_2^{\bullet} \xrightarrow{k_7} H_2O + O_2 + {}^{\bullet}OH$		$k_7 = 3.0\pm0.6$	Koppenol et al. (1978)
(2.36)	$HO_2^{\bullet} + {}^{\bullet}OH \xrightarrow{k_8} H_2O + O_2$		$k_8 = 7.1\times10^9$	Sehested et al. (1968)
(2.37)	$HCO_3^- + {}^{\bullet}OH \xrightarrow{k_9} CO_3^{\bullet-} + H_2O$		$k_9 = 8.5\times10^6$	Buxton et al. (1988)
(2.38)	$CO_3^{2-} + {}^{\bullet}OH \xrightarrow{k_{10}} CO_3^{\bullet-} + OH^-$		$k_{10} = 3.9\times10^8$	Buxton et al. (1988)
(2.39)	$CO_3^{\bullet-} + H_2O_2 \xrightarrow{k_{11}} HCO_3^- + HO_2^{\bullet}$		$k_{11} = 4.3\times10^5$	Crittenden et al. (1999)
(2.40)	$TOC + {}^{\bullet}OH \xrightarrow{k_7} intermediates \rightarrow CO_2 + H_2O$		$k_{12} = 7.0\times10^5$	Barrera (2011)
			$k_{13} = 1.1\times10^2$	**This study**

The quantum yield (ϕ) of a radiation-induced process is the number of times that a defined event occurs per photon absorbed by the system. This event may represent a chemical reaction and be calculable by Equations (2.41) and (2.42) (Shemer et al., 2006). In addition to radical recombination, the UVC/H_2O_2 process effectiveness is also delayed by the H_2O_2 low molar absorption coefficient, 18.6/M.cm at 254nm, which is responsible for large amounts of H_2O_2 being added to produce significant concentrations of $^{\bullet}$OH radicals within the system. Moreover, any post-treatment surplus of the H_2O_2 concentration should be removed from the effluent; otherwise, it could enter source waters, causing negative effects on fish and other living communities (Oppenländer, 2003; Black and Veatch, 2010).

$$\phi[M] = \frac{-d[M]/dt}{k_{s(\lambda)}} \tag{2.41}$$

$$k_{s(\lambda)} = \frac{q_0 \varepsilon_\lambda \left[1-10^{-\alpha_\lambda (r-R_i)}\right]}{\alpha_\lambda (r-R_i)} \tag{2.42}$$

where,

ϕ = quantum yield for TOC removal (mol/E);

t = time (s);

$k_{s(\lambda)}$ = specific rate of light absorption by TOC (E/mol.s);

q_0 = incident photon irradiance (E/cm^2.s);

ε_λ = molar absorption coefficient of TOC (1/M.cm);

α_λ = absorption coefficient (1/cm);

r = nominal radius of the photoreactor (cm); and

R_i = inner radius of the photoreactor (cm).

Bovine catalase is the most common compound used to remove excess H_2O_2, which converts H_2O_2 into water and oxygen, as shown in Reaction (2.43) (Chelikani et al., 2004). In particular, the low molar absorption coefficient and the use of compounds to control the H_2O_2 concentration in the effluent have a significant impact on the total cost of this AOP process.

$$2H_2O_2 \xrightarrow{bovine\ catalase} 2H_2O + O_2 \tag{2.43}$$

For a UV/H_2O_2 process to be efficient, the H_2O_2 concentration has to be at an optimal level to maximize the absorption of the incident photons, while the presence of other water compounds that may compete for the absorption of radiation must be minimized. The optimum H_2O_2 concentration also helps to minimize the recombination mechanisms as well as H_2O_2 effluent concentration surplus (Barrera, 2011).

The advantages of the UV/H_2O_2 process include a large range of applications, enhancing the degradation of pollutants, accelerating the rate of oxidation with great potentials for disinfection, and thorough mineralization of pollutants in wastewater (Stefan et al., 1996; Aye et al., 2004; Tabrizi and Mehrvar, 2004; De Morais and Zamora, 2005; Toor and Mohseni, 2007; Cao, 2009; Cao and Mehrvar, 2011; Barrera, 2011; Barrera et al., 2011). The successful applications of the UV/H_2O_2 process are shown in various wastewater treatment systems such as textile dye wastewater, with an optimum H_2O_2 concentration of 15 mM (Aye et al., 2003); atrazine wastewater, with 99% degradation in less than 15 min (Beltrán et al., 1993); linear alkyl benzene sulfonate (LAS) wastewater, with an optimum H_2O_2 concentration of 5,000 mg/L (Venhuis and Mehrvar, 2005); LAS wastewater in a pilot-plant photoreactor, with an optimum H_2O_2 concentration of 720 mg/L (Tabrizi and Mehrvar, 2006); cotton dyeing wastewater containing C.I. Direct Blue 199, with 80% of TOC removal in 2 h (Shu, 2006); and 99.99% of bacteria inactivation in 27.6 seconds (Barrera, 2011; Barrera et al., 2011). Important points should be considered while using the combination technique of UV photolysis with H_2O_2 for the wastewater treatment as recommended by Gogate and Pandit (2004b), including:

1. The synergism between UV photolysis and H_2O_2 is beneficial only for the contaminants that require a relatively higher level of oxidation conditions. It should be also noted that though the substrate removal rates are marginally affected, the overall degradation mechanism might be affected to a higher degree. An analysis in terms of COD and/or TOC removal should provide a better picture for the comparison of the efficacy of the hybrid technique as to against the individual technique.
2. The kinetic rate constants for the degradation process are observed to be inversely proportional to the initial concentration of the pollutant and hence dilution of the effluent stream should be done at an optimum level. It should be also noted that the net removal of the pollutant will be also dependent on the driving force available for the reaction and hence the exact dependency should be established with laboratory scale studies. On the other hand, it may even be observed at times

that absolutely no reduction in TOC is detected even for the combination technique. In such cases, a dilution factor of 10–15 may be also required before obtaining any appreciable degree of mineralization. For such cases, this method should only be used as a pre-treatment stage followed by biological oxidation or new hybrid methods consisting of additional oxidants, e.g. Fenton's reagent should be devised.

3. The concentration of H_2O_2 also needs to be properly selected. Usually, there is an optimum concentration, beyond which the presence of H_2O_2 is detrimental to the degradation reaction due to the scavenging action. Tanaka et al. (1989a; 1989b) reported that an optimum concentration of H_2O_2 is 0.01 M for the degradation of various organohalide compounds. Beltrán et al. (1993) have also reported an optimum concentration of H_2O_2 as 0.01 M for the degradation of atrazine. Wang and Hong (1999) reported that the photocatalytic degradation of 2-chlorobiphenyl in the presence of H_2O_2 is strongly inhibited above a particular concentration of H_2O_2 (0.1 M). The magnitude of the optimum H_2O_2 concentration depends on the level and type of the pollutants in the effluent stream, i.e., on the kinetic rate constant for the reaction between the free radicals and the pollutant and the rate constant for the recombination reaction. The optimum concentration of the H_2O_2 may be established using laboratory studies for the pollutant in question unless data are available in the literature with similar operating conditions.
4. A lower operating pH (in the range 2.5–3.5) is usually preferred for the combination technique of UV photolysis coupled with H_2O_2 and the exact value is dependent on the pH values for the contaminants in question. It should be noted here that the intrinsic rates of the UV/H_2O_2 process may not be affected much, but at a lower operating pH, the effect of the radical scavengers, especially ionic ones such as carbonate and bicarbonate ions, would be nullified leading to higher overall rates of degradation. Thus, it is better to have a lower operating pH. Mehrvar et al. (2001) explained the effect of $^{\bullet}OH$ scavenging, where the presence of some inorganic impurities may affect the photocatalytic destruction of organics in water and wastewater, since these anions scavenge hydroxyl radicals, which are responsible for attacking organics. Carbonate and bicarbonate ions are well known as hydroxyl radical scavengers, while phosphates, sulphates, and nitrates may also be present in the wastewater. Carbonate and bicarbonate ions react with hydroxyl radicals to produce carbonate radical ions as shown in Reaction (2.44) and (2.45). Moreover, decay of these carbonate radical ions might occur through Reaction (2.46) or (2.47).

$$HCO_3^- + {}^{\bullet}OH \xrightarrow{at\ low\ pH\ levels} CO_3^{\bullet -} + H_2O \qquad (2.44)$$

$$CO_3^{2-} + {}^{\bullet}OH \xrightarrow{at\ high\ pH\ levels} CO_3^{\bullet -} + OH^- \quad (2.45)$$

$$CO_3^{\bullet -} + CO_3^{\bullet -} \rightarrow CO_2 + CO_4^{-2} \quad (2.46)$$

$$CO_3^{\bullet -} + CO_3^{\bullet -} + H_2O \rightarrow 2CO_2 + HO_2^- + OH^- \quad (2.47)$$

5. The presence of radical scavengers is a crucial factor in deciding the overall efficiency of the process. Usually, there is an optimum concentration of the radical scavengers, below which the reduction in the rates of degradation is marginal. Cater (2000) reported that the optimum concentration of radical scavengers such as benzene, toluene, and xylene is 2 mg/L for the degradation of methyl tert-butyl ether; whereas, Ku et al. (1998) reported that humic acid strongly inhibits the degradation reaction only above the concentration of 8 mg/L. On the other hand, carbonate and bicarbonate ions inhibit the reaction even at lower concentrations (1–2 mg/L). Therefore, the optimum value of the concentration of radical scavengers is dependent on the pollutant-radical scavenger system, more specifically on the rate constant for the reactions between the pollutant-free radicals and scavenger-free radicals.
6. The presence of compounds such as humic acid, which results in strong absorption of incident UV light, is another factor that needs to be considered while adjusting the dose of H_2O_2. If these chemicals are present in the effluent stream, a higher dosage of H_2O_2 is required to achieve the synergistic effect.
7. Kinetic modeling of the degradation process is the key point in the effective design of photoreactors. A most realistic reaction model should consider all the chemical and photochemical reactions, the number may be even above 50–100, including the effects of the presence of radical scavengers and should be as rigorous as possible due to the observed major influence of other minor components.

The work of Crittenden et al. (1999) should serve as a useful guideline in developing realistic models for the prediction of overall rates in the degradation process. They have developed a kinetic model considering 44 different reactions using the reported kinetic rate constants and they have reported that the model fits the experimental results of 1,2-dibromo, 3-chloropropane degradation better as compared to the earlier model by Glaze et al. (1995) based on the pseudo-steady state

assumption, where net accumulation of free radicals is zero. According to Gogate and Pandit (2004b), the most realistic point in the developed model is the consideration of changing pH with time, considered for the first time. Usually operating pH is important in deciding the rates of reaction and it changes as the reaction proceeds.

Therefore, future work should be directed in developing realistic kinetic models and in establishing the optimum conditions for an H_2O_2 dose, the concentration of radical scavengers, and the pH for a variety of contaminants and mixtures. If the pertinent information is not available in the existing literature, laboratory scale studies with near identical geometric and operating conditions are recommended with the real effluents in question.

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/H_2O_2, can be modeled by the following simple mechanisms:

$$H_2O_2 \rightarrow 2\ {}^{\bullet}OH \qquad R_1 = \frac{\xi p}{V_T} \tag{2.48}$$

$${}^{\bullet}OH + TOC \rightarrow products \qquad R_2 = k_{TOC}[\ {}^{\bullet}OH][TOC] \tag{2.49}$$

$${}^{\bullet}OH + S_i \rightarrow products \qquad R_{3a} = k_{S_i}[\ {}^{\bullet}OH][S_i] \tag{2.50}$$

where,

R_1 = reaction rate of ${}^{\bullet}$OH (mg/L.h);

R_2 = reaction rate of ${}^{\bullet}$OH with TOC (mg/L.h);

R_3 = reaction rate of ${}^{\bullet}$OH with a scavenger (S_i) (mg/L.h);

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

p = power rating for the system (W);

V_T = treated SSWW volume (L);

S_i = a scavenger for the ${}^{\bullet}$OH, where i = a, b, …, n (mg/L); and

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

A steady-state analysis of this general mechanism yields the following overall rate kinetic for the UV/H_2O_2 process as shown in Equation (2.51). This simple mechanism is either zero- or first-order for TOC, if the concentration of TOC is high, $\left(k_{TOC}[TOC] \gg \sum_i k_{S_i}[S_i]\right)$, the reaction rate will be zero-order in TOC as shown in Equation (2.52). On the other hand, if the concentration of TOC is low, $\left(k_{TOC}[TOC] \ll \sum_i k_{S_i}[S_i]\right)$, the reaction rate will be first-order in TOC as shown in Equation (2.53). The difference between "high" and "low" concentration varies considerably with the system but is often approximately 100 mg/L (Bolton et al., 2001).

$$-\frac{d[TOC]}{dt} = \frac{\xi p k_{TOC}[TOC]/V_T}{k_{TOC}[TOC]+\sum_i k_{S_i}[S_i]} \tag{2.51}$$

$$-\frac{d[TOC]}{dt} = \frac{\xi p}{V_T} \tag{2.52}$$

$$-\frac{d[TOC]}{dt} = \frac{\xi p k_{TOC}}{V_T \sum_i k_{S_i}[S_i]} \tag{2.53}$$

2.4. Need for combined biological treatment and advanced oxidation processes

AOPs are becoming more appealing to serve as complementary treatment in either pre-treatment or post-treatment for current biological processes. Additionally, AOPs may inactivate bacteria without adding any additional chemicals to the wastewater in comparison to other techniques such as chlorination or ozonation processes that are commonly used in disinfection of water streams; thus, avoiding the possible formation of hazardous by-products (Tchobanoglous et al., 2003; Wang et al., 2006).

Meat processing industry effluents are included as a part of food industry wastewaters, and they constitute one of the greatest concerns of the agro-industrial sector due to the high amounts of water used in the process of slaughtering and further cleaning of the facility, approximately 62×10^6 m^3/year of water is consumed worldwide (de Sena et al., 2009; Oller et al., 2011). Nevertheless, only a small amount becomes a component of the final effluent; the remaining part has high biological and chemical oxygen demands, high fat content and high concentrations of dry waste, sediments and total suspended matter as well as nutrients (Masse and Masse, 2000b; Sroka et al., 2004; Debik and Coskun, 2009). AOPs have recently come into use for elimination and degradation, water reuse and

pollution control issues showing excellent overall results (Cao, 2009; de Sena et al., 2009; Cao and Mehrvar, 2011; Barrera, 2011; Barrera et al., 2011).

Further chemical oxidation in combined oxidation followed by biodegradation systems may not lead to any significant change in the molecular weight distribution. Hence, it is reasonable for pre-oxidation to be as short as possible and remove the biodegradable portion by cost-effective biological processes. Nonetheless, the amount of COD removable with this strategy may be limited, making use of longer oxidation necessary and the following biological process redundant (Poole, 2004). Internal recycling between the oxidation and biological stage has been recommended for reducing the chemical dose in such circumstances (Libra and Sosath, 2003).

If the original wastewater contains considerable amounts of biodegradable compounds, the pre-oxidation step obviously will not lead to a significant improvement of biodegradability; rather, it will only cause unnecessary consumption of chemicals (Oller et al., 2011). In such cases, a biological pre-treatment, removing biodegradable compounds, followed by an AOP, converting the non-biodegradable portion into biodegradable compounds with less chemical consumption is called for (Hörsch et al., 2003; Vidal et al., 2004). Such combined systems are particularly favourable for effluents such as olive mill wastewater or landfill leachates, which initially contain some biodegradable fractions (i.e. sugars and proteins) which could easily be removed first and so, not compete for the chemical oxidant.

A recent study by Cao (2009) found that the combined processes of ABR and UV/H_2O_2 photoreactor are highly efficient for the treatment of SSWW at a laboratory scale, with maximum TOC, COD, and $CBOD_5$ removal efficiencies of 89.9, 97.7, and 96.6%, respectively, for an influent TOC concentration of 973.3 mg/L at a HRT of 3.8 days in the ABR compartments (Cao 2009; Cao and Mehrvar, 2011). However, the results showed that the TN concentrations in the combined processes had no significant changes (no more than 6% change); thus, the combined processes were not able to remove TN from the wastewater effectively. Furthermore, there was no evidence to show sequential nitrogen removal including aerobic nitrification and anaerobic denitrification. In summary, for the biological removal of nutrients (N and P), an adequate combination of anaerobic and aerobic processes is essential. An overview of the most frequently applied technologies and combined reactors is outlined in Table 2.15, with specific attention to the evaluation of their treatment efficiencies in terms of organic removal.

Table 2.15. Anaerobic–aerobic and UV/H_2O_2 systems for the treatment of wastewater.

Reactor Type[1]	Processes[2]	Type of wastewater[3]	HRT[4] (h)	TOC_{in}* (mg/L)	BOD_{in} (mg/L)	TN_{in} (mg/L)	TOC* removal (%)	BOD removal (%)	TN removal (%)	Reference
RBC + SBR	Ana-Ae	Screened dairy manure	24-96	28300-40100	390-2045	110-313	86.1-98	88.5-92.5	54.7-95.5	Lo and Liao (1986)
UASB	Ana	Slaughterhouse	1.7-10	1500-2200	490-650	120-180	40-91	-	-	Sayed et al. (1987)
AnFB	Ana	Slaughterhouse, dairy and brewery	8	430-850	-	4.8	50-80	-	-	Toldrá et al. (1987)
UASB	Ana	Slaughterhouse	12-40	1925-11118	490-650	110-240	68.4-82.3	85-90	24	Sayed and Zeeuw (1988)
TAT	Ae	Slaughterhouse	6-30	3015	1905	14.3	69-95.5	90	2.1-52.2	Gariepy et al. (1989)
RBC + SBR	Ana-Ae	Mixture of cheese whey and dairy manure	48-120	36000-65700	282-470	28-38.2	99	80-95	26-99	Lo and Liao (1989)
AnaFB + ALSR	Ana-Ae	Complex Industrial	72-1176	3600-3900	-	140	60-65	-	96-98	Heijnen et al. (1991)
BCDT	Ana-Ae	Synthetic	3-11	-	-	20	-	-	90	Hano et al. (1992)
ABR	Ana	Slaughterhouse	2.5-26	450-730	-	-	75-90	-	20-27	Polprasert et al. (1992)
AnaFB	Ana	Slaughterhouse	36-96	7500	-	-	27-85	-	-	Tritt (1992)
IAAFBR	Ana-Ae	Municipal	24	350	-	-	80	-	-	Fdez-Polanco et al. (1994)
VUV	AOPs	Atrazine effluent	6.7	10	-	-	65-90	-	-	Gonzalez and Braun (1994)
UASB + AF	Ana-Ae	Slaughterhouse	2-12	2450	1550	150	96	-	-	Borja et al. (1995a)
AnaFB	Ana	Slaughterhouse	0.5-8	250-4500	3120	310	75-98.9	-	-	Borja et al. (1995b)
HB + AS	Ana-Ae	Oil shale ash dump leachate	211.2	2000-4600	810-2700	27-45	67-74	99	75-78.6	Kettunen and Rintala (1995)
ABR	Ana	Palm oil mill	60	15103-65100	8200-35400	12-126	33.1-84.6	41.7-86	7.6-30.3	Setiadi et al. (1996)
AAGBR	Ana-Ae	Synthetic	48	3030-3650	-	-	95-98	-	-	Shen and Guiot (1996)
ABR	Ana	Slaughterhouse	20	4000	-	-	75-95	-	-	Nachaiyasit and Stuckey (1997)
UASB + AF	Ana	Slaughterhouse	28.8-156	5200-11400	-	19-74	44.9-97	-	95-98.4	Ruiz et al. (1997)
ABR	Ana	Swine waste	336-1008	59400	-	1682	70-78	-	48-55	Boopathy (1998)
ARSBFB	Ana	Slaughterhouse	0.5-1.5	10410	6600	230	90.2-96.2	-	-	Borja et al. (1998)
UASB + RBC	Ana-Ae	Domestic sewage	3-9	363-666	240-333	-	82.4-98.9	88.9-97.4	-	Castillo et al. (1999)
ABR	Ana	Pulp and paper mill black liquors	48	32000-40000	12000-16000	750-1000	54-70	-	-	Grover et al. (1999)
MMHR	Ana-Ae	Degradation of PCE and TCE	12-72	-	-	-	-	-	-	Miguez et al. (1999)
EGSB	Ana	Slaughterhouse	-	1440-4200	1100-2400	-	65-80	-	-	Núñez et al. (1999)
GRABBR	Ana	Whiskey distillery	48-240	9500	3755	-	80-92.3	90.6-96.1	-	Akunna and Clark (2000)
AFFFBR	Ana	Slaughterhouse	3.5-31	1100-11300	600-1700	100-300	85-95	-	-	Del Pozo et al. (2000)
ABR	Ana	Diluted, soluble and colloidal	1.3-80	500	-	-	40-95	-	-	Langenhoff et al. (2000)

Reactor Type[1]	Processes[2]	Type of wastewater[3]	HRT[4] (h)	TOC_{in}* (mg/L)	BOD_{in} (mg/L)	TN_{in} (mg/L)	TOC* removal (%)	BOD removal (%)	TN removal (%)	Reference
SBR	Ana	Slaughterhouse	-	6908-11500	-	-	90-96	-	-	Masse and Masse (2000a)
DAF + UASB	Ae-Ana	Slaughterhouse	4-10	1100-7250	600-3900	90-150	70-90	-	-	Manjunath (2000)
UASB + AFBR	Ana-Ae	Synthetic textile	20	2700	-	-	75	-	-	Yu et al. (2000)
BPCR + O_3	Ae-AOPs	PAHs	0.83	436	-	-	91.7	-	-	Zeng et al. (2000)
CSTR + AS	Ana-Ae	Green olive debittering	1320	16500-23500	-	500-750	83.5	-	-	Aggelis et al. (2001)
UV/H_2O_2/Fe(II) + AS	AOPs-Ae	Semi-conductor industry	12-72	145-2760	-	-	90	-	-	Park et al. (2001)
UV/H_2O_2/Fe(III)/TiO_2 + FBR	AOPs-Ae	Industrial	3.5	-	-	-	80.3	-	-	Sarria et al. (2001)
UASB + AS	Ana-Ae	Municipal	6.8	386-958	-	-	85-93	-	-	Sperling et al. (2001)
AAGBR	Ana-Ae	Degradation of Aroclor 1242	50.4	-	-	-	-	-	-	Tartakovsky et al. (2001)
UASB + CSTR	Ana-Ae	Pulp and paper industry effluent	11.54	5500-6600	900-1650	-	91	50-94	-	Tezel et al. (2001)
O_3 + SBBR	AOPs-Ae	Tannery	8	3500-4000	2000-2400	200-300	97	-	98	Di Iaconi et al. (2002)
FBP + CC/EO	Ae-AOPs	Textile	3	800-1000	-	-	95.4	-	-	Kim et al. (2002)
UV/H_2O_2/Fe(II) + AS	AOPs-Ae	PAHs	216	-	-	-	80-85	-	-	Nadarajah et al. (2002)
ABR	Ana	Ice-cream	10.3-240	6200	3450	25	99	-	-	Uyanik et al. (2002)
ABR	Ana	Textile	20	4000	-	-	90	-	-	Bell and Buckley (2003)
AS + O_3	Ae-AOPs	Cork processing industry	24-72	10000-40000	-	-	31-85	-	-	Benitez et al. (2003a)
AS + O_3 + SBR	Ae-AOPs-Ae	Cork processing industry	3-72	10000-40000	-	-	25-91	-	-	Benitez et al. (2003b)
ABR + AS	Ana-Ae	Municipal	13.5-15.2	300	162	38.4	78.6-83	92.5-94	46.4-87.3	Bodík et al. (2003)
FFB + FFB	Ana-Ae	Slaughterhouse	112.8-175.2	400-1600	200-650	105-320	92	99	95	Del Pozo and Diez (2003)
ABR	Ana	Slaughterhouse	112.8-175.2	7230	3180	690	92	99	-	Del Pozo et al. (2003)
MBR	Ana	Synthetic, Vegetables and Slaughterhouse	1.2	5800-64600	2200-24200	301-1580	97	-	-	Fuchs et al. (2003)
Ultrasound + AS	AOPs-Ae	Raw paper mill	24-168	600-15000	220	-	73-83	93.2-99	-	Gonze et al. (2003)
UV/H_2O_2/Fe(III) + FBR	AOPs-Ae	Industrial	2-5	-	-		90	-	-	Sarria et al. (2003)
UASB + AS	Ana-Ae	Starch Industry	120	20000	-	1000	77-93	-	90	Sklyar et al. (2003)
UASB	Ana	Slaughterhouse	2-7	3265-14285	914-1917	35-104	75-90	-	-	Torkian et al. (2003)
EO + FBR	AOPs-Ae	Industrial	3-24	14350	136	6.8	94	-	-	Torres et al. (2003)
SFABR	Ana	Brewery	48	85000	-	411.6	90	-	-	Uyanik (2003)
ABR	Ana	Synthetic	24	3000	-	-	86	-	-	Vossoughi et al. (2003)
UASB + AFBR	Ana-Ae	Synthetic textile	2.7-32.7	2000-3000	-	-	-	-	-	Chen (2004)
ABR	Ana	Sanitation on-site	22	564	-	-	58	-	-	Foxon et al. (2004)

Reactor Type[1]	Processes[2]	Type of wastewater[3]	HRT[4] (h)	TOC_{in}* (mg/L)	BOD_{in} (mg/L)	TN_{in} (mg/L)	TOC* removal (%)	BOD removal (%)	TN removal (%)	Reference
UASB + CSTR	Ana-Ae	Cotton textile mill	138	604-1038	-	-	40-85	-	-	Isik and Sponza (2004)
BCR + UV/H_2O_2/Fe(II)	Ae-AOPs	Food industry	48	300-16200	100-6600	-	69.3	-	-	Kotsou et al. (2004)
UAAFBIR	Ana-Ae	Synthetic	9	365-3500	-	245.5	95-98	-	-	Moosavi et al. (2004)
SBR + MBR	Ae-RO	Slaughterhouse	12	2780-6720	1200-3000	49-287	98.1	99.6	98.2	Sroka et al. (2004)
UASB + CSTR	Ana-Ae	Food solid waste leachate	138	5400-20000	405-841	258-679	96-98	92.9-93.8	99.6	Agdag and Sponza (2005)
O_3 + BABS	AOPs-Ae	Paper mill	-	1586.3	282.2	-	50	50	-	Bijan and Mohseni (2005)
SBR	Ae	Slaughterhouse	72	7685	-	1057	98.6	-	97.4	Cassidy and Belia (2005)
IAAFFR	Ana-Ae	Slaughterhouse	22.56-91.2	1190-2800	610-1150	150-260	93	97	69	Del Pozo and Diez (2005)
RAAIBB	Ana-Ae	Sewage	1.2-15.5	345	-	41	84	-	96	Garbossa et al. (2005)
ABR + CSTR	Ana-Ae	Synthetic	249.1	3000	-	-	92	-	-	Kuşçu and Sponza (2005)
AASBR + FBNR	Ana-Ae	Slaughterhouse	15	7780	-	88	99	-	85	Merzouki et al. (2005)
PC + AS	Ana-Ae	Textile	22-82	800-1200	-	7-21	50-85	-	-	Kapdan and Alparslan (2005)
SBR + EO	Ae-AOPs	Food industry	168	8000-35000	3500-20000	1000-2000	98	-	-	Kyriacou et al. (2005)
AdNR	Ana	Slaughterhouse	-	614.5	-	163.7	-	-	95	Reginatto et al. (2005)
AS + EO	Ae-AOPs	Tannery	0.25	2386-3000	-	292-426	99	-	99.7	Szpyrkowicz et al. (2005)
AAGBR	Ana-Ae	TCE effluent	17-20	800	-	-	-	-	-	Tartakovsky et al. (2005)
SAAMB	Ana-Ae	Synthetic	72.7	1300-10500	-	110-1220	97-99	-	26-99	Zhang et al. (2005)
O_3 + SBR	AOPs-Ae	Paper mill	24	455-1145	109.2-194.7	-	37-90	-	-	Balcioğlu et al. (2006)
AS + O_3	Ae-AOPs	Tannery	7.8	2420	-	140	15-38	-	-	Dogruel et al. (2006)
UASB + AS	Ana-Ae	Olive mill + municipal	28.3	1800-4400	-	-	75-95	-	-	Gizgis et al. (2006)
UV/H_2O_2	AOPs	NOM in groundwater	0.25	17.5	-	-	85-94	-	-	Goslan et al. (2006)
UASB + CSTR	Ana-Ae	Wool acid dying	79.2	499-2000	-	-	83-97	-	-	Isik and Sponza (2006)
ABR + CSTR	Ana-Ae	Synthetic	249.1	3000	-	133	80-99	-	77.4	Kuşçu and Sponza (2006)
AS + MBR	Ana-Ae	Municipal	5.8-7.9	356-371	171-209	60.7-62.3	55.3-91.6	98.1-99.9	83.9	Mouthon-Bello and Zhou (2006)
ABR + BASR	Ana-Ae	Pharmaceutical	5-60	9736-19862	350-8600	-	85.3-91.2	-	-	Zhou (2006)
UBF + MBR	Ana-Ae	Synthetic	24	6000-14500	-	300-1000	99	-	46	Ahn et al. (2007)

Reactor Type[1]	Processes[2]	Type of wastewater[3]	HRT[4] (h)	TOC_{in}* (mg/L)	BOD_{in} (mg/L)	TN_{in} (mg/L)	TOC* removal (%)	BOD removal (%)	TN removal (%)	Reference
UV/H_2O_2 + AS	AOPs-Ae	Textile	1-2	500	-	-	86.4-99	-	-	Arslan-Alaton et al. (2007)
$UV/H_2O_2/Fe(II)$ + AS	AOPs-Ae	COCs	168-1344	126	-	-	80	-	-	Kastanek et al. (2007)
UASB + ASCS	Ana-Ae	Municipal	3.53-6.2	341	-	-	82.7-88.3	-	-	La Motta et al. (2007)
ARB + EO	Ana-AOPs	Landfill leachate	3	16271	9100	1860	98.5	99.9	64.2-99.9	Lei et al. (2007)
UV/H_2O_2	AOPs	Trichloroethene	0.5	-	-	-	70	-	-	Li et al. (2007)
AFFFBR + AS	Ana-Ae	PTA effluent	23-27.2	5000	-	-	96.4	-	-	Pophali et al. (2007)
UASB + CSTR	Ana-Ae	Pharmaceutical	-	3000	120-400	-	97	-	-	Sponza and Demirden (2007)
UV/H_2O_2 + BAC	AOPs-Ae	DBPs	-	-	-	-	52-99	-	-	Toor and Mohseni (2007)
UASB + UV/TiO_2	Ana-AOPs	Dairy	6	5000	2800	16.5	95	-	-	Banu et al. (2008)
ABR + $O_3/UV/H_2O_2/Fe(II)$	Ana-AOPs	Textile	72	250-3135	-	-	92-97	-	-	García-Montaño et al. (2008)
UASB + CSTR	Ana-Ae	Simulated textile	19.2-29.3	4214	3120	-	91-97	-	-	Isik and Sponza (2008)
AS + UV/TiO_2	Ae-AOPs	High salinity	25	200	-	-	98	-	-	L'Amour et al. (2008)
MBR + O_3	Ae-AOPs	Paper mill	72	326	158	-	70	-	-	Mänttäri et al. (2008)
HAD + UV/TiO_2	Ana-AOPs	NOM	288	1.85	-	100	-	-	96	Rizzo et al. (2008)
$UV/H_2O_2/Fe(II)$ + IBR	AOP-Ae	Surfactant	5-20	1500-1533	332-367	-	94	-	-	Wang et al. (2008)
SAAB	Ana-Ae	Diluted landfill leachate	-	1000-3300	-	80-230	94	-	95	Yang and Zhou (2008)
EGSB + ABFR	Ana-Ae	POME	72	32520	-	644	95.6	-	99.3	Zhang et al. (2008)
ABR + O_3	Ana-AOPs	MTE	336.5	958	290	-	97	92.7	-	Artanto et al. (2009)
AS + O_3	Ae-AOPs	Paper mill	6-20	1500-22500	-	-	75.5-80	-	-	Assalin et al. (2009)
AS + UV/TiO_2	Ae-AOPs	Industrial	72	1599	-	-	62	-	-	Barreto-Rodrigues et al. (2009)
SBR + $UV/H_2O_2/Fe(II)$	Ae-AOPs	Swine	24	5417	-	1130	97.3	-	96.5	Ben et al. (2009)
$UV/H_2O_2/Fe(II)$ + FBR	AOPs-Ae	Plastic products	1	-	-	-	72-73.6	33.9	-	Chen et al. (2009)
DAF + $UV/H_2O_2/Fe(II)$	Ae-AOPs	Slaughterhouse	0.5	2800-3000	1400-1600	-	80.3-97.6	70.3-95.7	-	de Sena et al. (2009)
WL + $UV/H_2O_2/TiO_2$	Ae-AOPs	Biologically pre-treated grey-water	0.2	5.5	-	-	63.6	-	-	Gulyas et al. (2009)
Fungi + $UV/H_2O_2/Fe(II)$	Ana-AOPs	Olive Oil Mill wastewater	1	220	-	-	77	-	-	Justino et al. (2009)
UV + UV/H_2O_2	AOPs	Pharmaceutical	-	-	-	-	86-99	-	-	Kim et al. (2009a)
UV + UV/H_2O_2	AOPs	Pharmaceutical and PCP	-	-	-	-	90	-	-	Kim et al. (2009b)
O_3 + BAC + CDI	AOPs-Ae-DI	RO brine	0.33	15.6-44.2	5.4	-	31.5-88.7	-	-	Lee et al. (2009)
UV/H_2O_2	AOPs	Slaughterhouse	-	-	-	-	95	-	-	Luiz et al. (2009)
$UV/H_2O_2/Fe(II)$ + AS	AOPs-Ae	PAHs	12	-	-	-	25	-	-	Rafin et al. (2009)

Reactor Type[1]	Processes[2]	Type of wastewater[3]	HRT[4] (h)	TOC_{in}* (mg/L)	BOD_{in} (mg/L)	TN_{in} (mg/L)	TOC* removal (%)	BOD removal (%)	TN removal (%)	Reference
IBR + UV/H_2O_2/Fe(II)	Ae-AOPs	Pharmaceutical	26	3400	-	0.1	90	-	90	Sirtori et al. (2009)
MBR/BAC + UV/O_3	Ae-AOPs	Drinking water	1.3	-	-	-	40-60	-	-	Treguer et al. (2009)
AAIBR	Ana-Ae	Potato starch	6-24	1100-4500	-	-	88.4-98.7	-	-	Wang et al. (2009a)
AnaF + ACOT + PChR	***Ana-Ae-AOPs***	***Landfill leachate***	***48***	***2000-10000***	***230-700***	***720-4500***	***90.5-94.8***	***-***	***89-90.6***	***Wang et al. (2009b)***
UV/H_2O_2	AOPs	Insecticide	2	-	-	-	97	-	-	Abramović et al. (2010)
VUV + UV + UV/H_2O_2	AOPs	Neurotoxins effluent	6.63	6.63	-	-	50-88	-	-	Afzal et al. (2010)
UV + UV/H_2O_2	AOPs	Tetracycline's effluent	2	67.1	-	-	88.9	-	-	López-Peñalver et al. (2010)
MBR + O_3	Ae-AOPs	Pharmaceutical	1	10900	-	420	99	-	-	Mascolo et al. (2010)
UV/H_2O_2	AOPs	Per-fluorinated Surfactants	2-960	100	-	-	60	-	-	Quinete et al. (2010)
ABR + O_3	Ana-AOPs	Pharmaceutical	27	22	-	-	90	-	-	Reungoat et al. (2010)
AS + O_3	Ae-AOPs	Municipal	-	269	42	14.7	78.1	81.4	42.2	Rosal et al. (2010)
UV/H_2O_2	AOPs	Pharmaceutical	-	6.6-10.3	-	0.2-14.8	90	-	-	Rosario-Ortiz et al. (2010)
AS + O_3	Ae-AOPs	Pharmaceutical	2-22	139	49	33	75.5	91.8	70.3	Schaar et al. (2010)
O_3 + BAC	AOPs-Ae	THMs and NOM	168-240	3.8-4.5	-	-	51	-	-	Yan et al. (2010)
ABR + UV/H_2O_2	***Ana-AOPs***	***Synthetic Slaughterhouse***	***76.3-91.2***	***2110-2305***	***1020-1143***	***80-334***	***97.7***	***96.6***	***1-6***	***Cao 2009; Cao and Mehrvar (2011)***
UV + VUV + H_2O_2	AOPs	Synthetic Slaughterhouse	2.5	1000	-	-	57.6	-	-	Barrera (2011); Barrera et al. (2011)
O_3 + UV/H_2O_2	AOPs	Pharmaceutical and PCP	-	-	-	-	90	-	-	Kim et al. (2011)
ABR + AS + UV/H_2O_2	**Ana-Ae-AOPs**	**Synthetic Slaughterhouse**	**74.9-168**	**941-1009**	**640**	**254-428**	**89.5-99.9**	**99.7**	**76.4-81.6**	**This study**

[1] Reactor Type: AAGBR, anaerobic-aerobic granular biofilm reactor; AAIBR, anaerobic-aerobic integrative baffled reactor; AASBR, anaerobic-anoxic sequencing batch reactor; ABFR, aerobic biofilm reactor; ABR, anaerobic baffled reactor; ACOT, aerobic contact oxidation tank; AdNR, anaerobic denitrifying reactor; ARSBFB, anaerobic reactor with sludge blanket and filter bed; AS, activated sludge; AF, anaerobic filter; AFBR, anaerobic fluidized bed reactor; AFFFBR, anaerobic fixed film fixed bed reactor; ALSR, air lift suspension reactor; AnF, anaerobic filter; AnFB, anaerobic fluidized bed; ARB, aged-refuse biological reactor; ASCS, aerobic solid contact system; BABS, batch aerobic biological system; BAC, biological activated carbon; BASR, biofilm airlift suspension reactor; BCDT, bubble column with a draught tube; CDI, capacitive deionization; CSTR, continuously stirred tank reactor; DAF, dissolved air flotation; EGSB, expanded granular sludge bed; EO, electrochemical oxidation; FBNR, fixed bed nitrification reactor; FBR, fixed bed biological reactor; FFB, fixed film bioreactor; GRABBR, granular-bed anaerobic bed reactor; HAD, heterotrophic-autotrophic denitrification; HB, hybrid bioreactor; IAAFBR, integrated anaerobic-aerobic fluidized bed reactor; IAAFFR, integrated anaerobic-aerobic fixed film reactor; IBR, immobilised biomass reactor; MBR, membrane bioreactor; MMHR, methanogenic-methanotrophic hybrid reactor; PCR, packed column reactor; PChR, photochemical reactor; RAAIBB, radial anaerobic/aerobic immobilized biomass bioreactor; RBC, rotating biological contactors; SAAB, simultaneous aerobic and anaerobic bioreactor; SAAMB, staged anaerobic-aerobic membrane bioreactor; SBR, sequencing batch reactor; SBBR, sequencing biofilm batch reactor; SFABR, split fed anaerobic baffled reactor; TAT, thermophilic aerobic treatment; UAAFBIR, upflow anaerobic/aerobic fixed bed integrated reactor; UASB, upflow anaerobic sludge bed; UBF, upflow bed filter; WL, wetland; BCR, bubble column reactor; IBR, immobilised biomass reactor; FBP, fluidized biofilm process; CC/EO, chemical coagulation/electrochemical oxidation; EO, electrochemical oxidation.

[2] Process Type: Ae, aerobic; Ana, anaerobic; AOP, advanced oxidation process; DI, deionization; RO, reverse osmosis.

[3] Type of waste water: COCs, chlorinated organic compounds; DBPs, disinfection by-products; MTE, mechanical thermal expression; NOM, natural organic matter; PAHs, polycyclic aromatic hydrocarbons; PCE, tetrachloroethylene; PCP, personal care products; POME, palm oil mill effluent; PTA, purified terephthalic acid; TCE, trichloroethylene; THMs, trihalomethanes.

[4] HRT, Hydraulic retention time.

* COD was analysed in some cases instead of TOC.

2.5. Concluding remarks

It may be stated that it is operationally and economically advantageous to adopt anaerobic–aerobic processes in the treatment of high strength industrial wastewaters since it couples the benefit of anaerobic digestion in high-strength wastewater with the benefits of aerobic digestion with better COD and VSS removal (Ros and Zupancic, 2004), as well as using AOPs such as UV/H_2O_2 as a post-treatment alternative.

This chapter has shown several examples of combined biological and photochemical treatment, including the studies by Cao (2009), Wang et al. (2009b) and Cao and Mehrvar (2011), who investigated the treatment of industrial wastewater using a combined photo-oxidation and biological treatment with a higher rate of TOC removal as compared with other processes, reaching removal rates of COD, TOC, BOD, and TN up to 95, 96, 99 and 80%, respectively, as well as the complete disinfection and bacterial inactivation completed by the photochemical process as a post-treatment stage (Barrera, 2011; Barrera et al., 2011). Therefore, a combined anaerobic-aerobic and UV/H_2O_2 system was chosen for the treatment of SSWW in this study. Results obtained from this work will help to extend the information on the combined biological and AOPs process, its performance and effectiveness in removing TOC, TN, and BOD from slaughterhouse wastewater.

CHAPTER 3

MATERIALS AND METHODS

3.1. Introduction

This study is focused on determining the performance and the treatment ability of the ABR, the aerobic AS, and the UV/H_2O_2 processes, as well as their combination for the removal of TOC, TN, and BOD from synthetic SSWW. To that end, experiments were conducted in order to assess the efficiencies and performance of such processes. The study consists of different configurations of the combined anaerobic-aerobic and UV/H_2O_2 processes for the treatment of SSWW, interchanging their order for obtaining more information that is accurate about the behaviour of each configuration in the treatment of SSWW. In this chapter, an overall description of the research approach, materials, and procedures is presented.

3.2. Materials

3.2.1. Synthetic slaughterhouse wastewater (SSWW)

The wastewater in this study was the SSWW, prepared in accordance with the previous studies (Cao, 2009; Cao and Mehrvar, 2011; Barrera, 2011; Barrera et al., 2011), and based on the recipe developed by Stephenson and Lester (1986) in order to compare the main differences between the results found in the new configurations and those of the previous studies. The SSWW contains (Table 3.1) commercial meat extract powder (Oxoid Lab Lemco L0029, Oxoid Ltd.), whose components are listed in Table 3.2; glycerol ($C_3H_8O_3$); ammonium chloride (NH_4Cl); sodium chloride (NaCl); potassium dihydrogen orthophosphate (KH_2PO_4); calcium chloride ($CaCl_2$); and magnesium sulphate heptahydrate ($MgSO_4 \bullet 7H_2O$). The pH values and the concentrations of TOC, TN, and $CBOD_5$ were measured to investigate the characteristics of the SSWW and these were compared against the results found in the open literature. A hydrogen peroxide solution (1,110 g/L density) containing 30%w/w of H_2O_2 was used in the UV/H_2O_2 process.

Table 3.1. Synthetic slaughterhouse wastewater recipe.

(Adapted from Stephenson and Lester 1986).

Component	Concentration (mg/L *dw**)
Commercial meat extract powder (Oxoid Lab Lemco L0029, Oxoid Ltd.)	1950
Glycerol ($C_3H_8O_3$)	200
Ammonium chloride (NH_4Cl)	360
Sodium chloride (NaCl)	50
Potassium dihydrogen orthophosphate (KH_2PO_4)	30
Calcium chloride ($CaCl_2$)	24
Magnesium sulphate ($MgSO_4 \cdot 7H_2O$)	7.5

* *dw*, distilled water.

Table 3.2. Components of the meat extract powder provided by the manufacturer (Oxoid Ltd.)

Symbol	Amino acid	%w/w
Ala	Alanine ($C_3H_7NO_2$)	5.85
Arg	Arginine ($C_6H_{14}N_4O_2$)	7.10
Asp	Aspartic acid ($C_4H_7NO_4$)	5.10
Cys	Cysteine ($C_3H_7NO_2S$)	0.68
Glu	Glutamic acid ($C_5H_9NO_4$)	10.71
Gly	Glycine ($C_2H_5NO_2$)	10.85
Ile	Isoleucine ($C_6H_{13}NO_2$)	3.17
Leu	Leucine ($C_6H_{13}NO_2$)	3.15
Lys	Lysine ($C_6H_{14}N_2O_2$)	4.78
Met	Methionine ($C_5H_{11}NO_2S$)	2.61
Phe	Phenylalanine ($C_9H_{11}NO_2$)	2.34
Pro	Proline ($C_5H_9NO_2$)	7.79
Ser	Serine ($C_3H_7NO_3$)	1.87
Thr	Threonine ($C_4H_9NO_3$)	2.54
Trp	Tryptophan ($C_{11}H_{12}N_2O_2$)	0.34
Tyr	Tyrosine ($C_9H_{11}NO_3$)	0.66
Val	Valine ($C_5H_{11}NO_2$)	3.06
Total		***72.60***

3.2.2. Anaerobic and aerobic inoculum

The anaerobic and aerobic sludge seeds (37,500 mgSS/L) were obtained from the Ashbridges Bay Wastewater Treatment Plant, a municipal wastewater treatment plant in Toronto, Ontario,

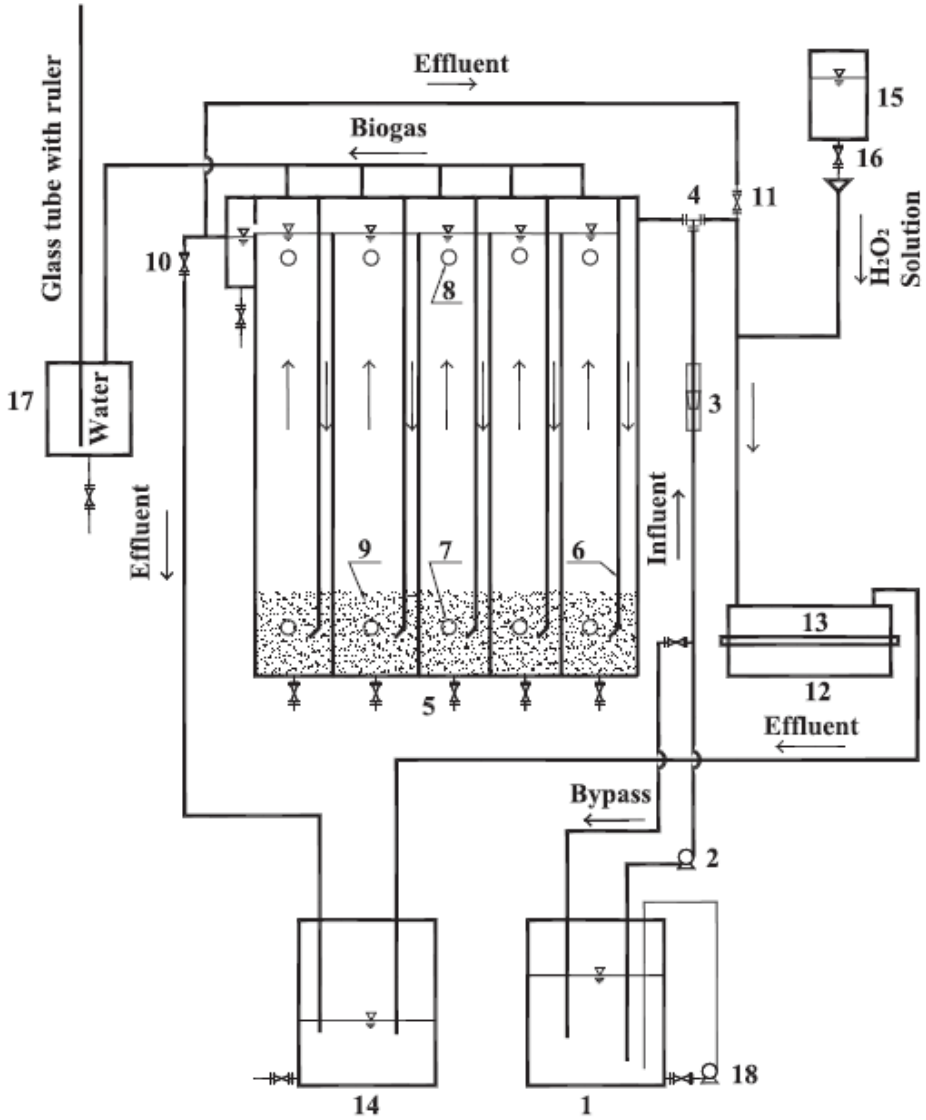
Canada. A total of 10 L of the anaerobic sludge seed was loaded into the ABR (about 2 L in each compartment) whereas, 5 L of the aerobic sludge seed were loaded into the aerobic AS reactor. The inoculum (2.5 gVSS/L) in the compartments was acclimatized to the SSWW by feeding the wastewater continuously into the reactors. Excess of the supply of sludge was stored in a closed container and fed by SSWW periodically at room temperature for future usage.

3.3. Experimental setup

Combined processes consisted of two stages: a biological process using an ABR and a UV/H_2O_2 process developed by Cao and Mehrvar (2009, 2011) as shown in Figure 3.1. Considering the relatively high biodegradability of the SSWW, the ABR is placed before the UV photoreactor.

The ABR consists of 5 equal-volume compartments with individual gas headspaces. Each compartment is further divided into two small chambers (2 and 8 cm in width, respectively) by a 45° slanted edge baffle leading to downflow and upflow of the wastewater, which provided effective mixing and contact time between the wastewater and the biomass within each compartment (Kuşçu and Sponza, 2006; Uyanik et al., 2002). No additional mixing was supplied in all compartments. The total working volume of the ABR was 33.7 L (total of 50, 15, and 50 cm of length, width, and height, respectively). The wastewater sampling ports were located 40 cm from the bottom of each compartment and 4 cm from the side of its slanted edge baffle, while the sludge sampling ports were located at 10 cm from the bottom of each compartment and 4 cm from the side of its slanted edge baffle.

The stainless steel UV photoreactor (Siemens – Wallace & Tiernan® UV Disinfection Systems, Barrier® SL-1S) had a total working volume of 1.35 L (8 cm external diameter and 34 cm length). A UV lamp (output power: 6 W, wavelength: 254 nm, and diameter: 2.5 cm) was inserted into the center of the cylindrical photoreactor. The UV lamp was covered by a quartz sleeve in order to protect the lamp from fouling that may interfere with the UV radiation emission. Figure 3.2 shows the schematic diagram of the UV photoreactor.



1) Wastewater feed tank
2) Peristaltic pump
3) Flow meter
4) 3-way valve
5) Anaerobic baffled reactor
6) Slanted edge baffle
7) Sludge sampling valve
8) Wastewater sampling valve
9) Anaerobic Sludge
10) 2-way valve
11) 2-way valve
12) UV photoreactor
13) UV lamp
14) Treated wastewater collection tank
15) H_2O_2 solution container
16) Flowrate control valve
17) Gas collection container
18) Recirculating pump

Figure 3.1. Schematic diagram of the combined processes of ABR and UV/H_2O_2 photoreactor.
(Adapted from Cao, 2009; Cao and Mehrvar, 2011).

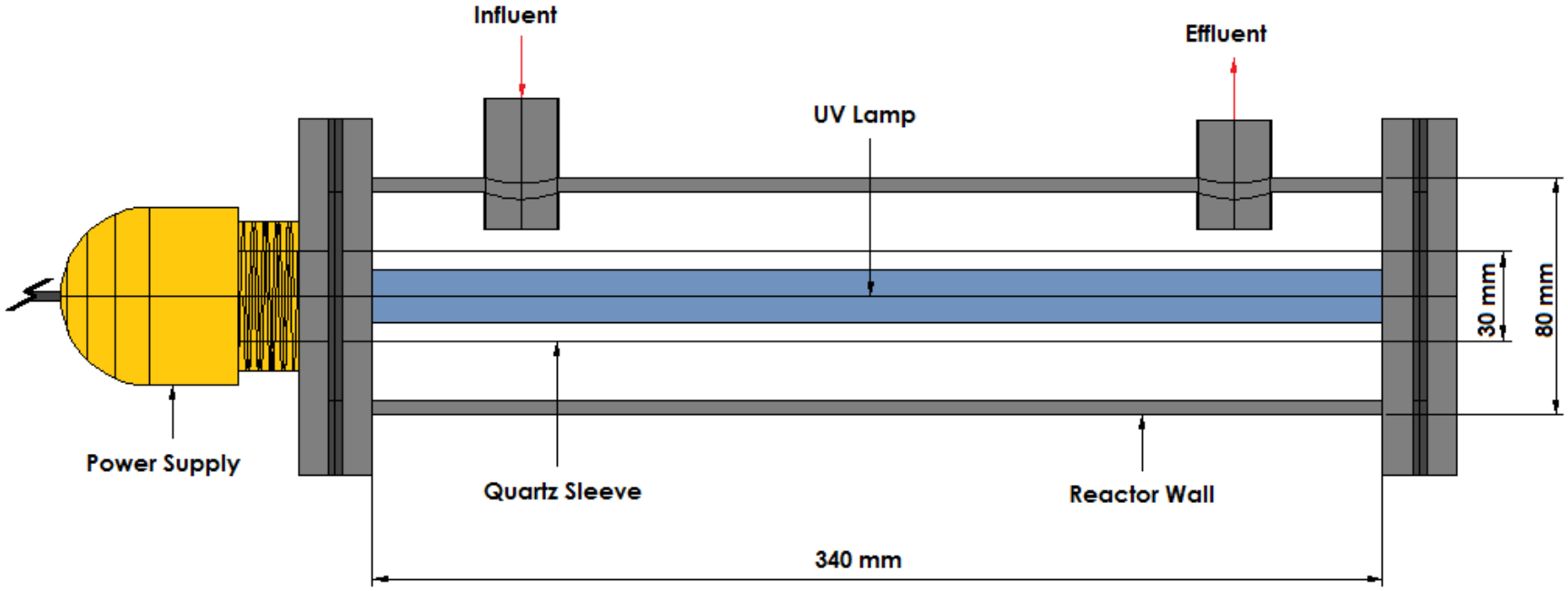


Figure 3.2. Schematic diagram of the individual UV photoreactor (Siemens, Barrier® SL-1S), V=1.35L.

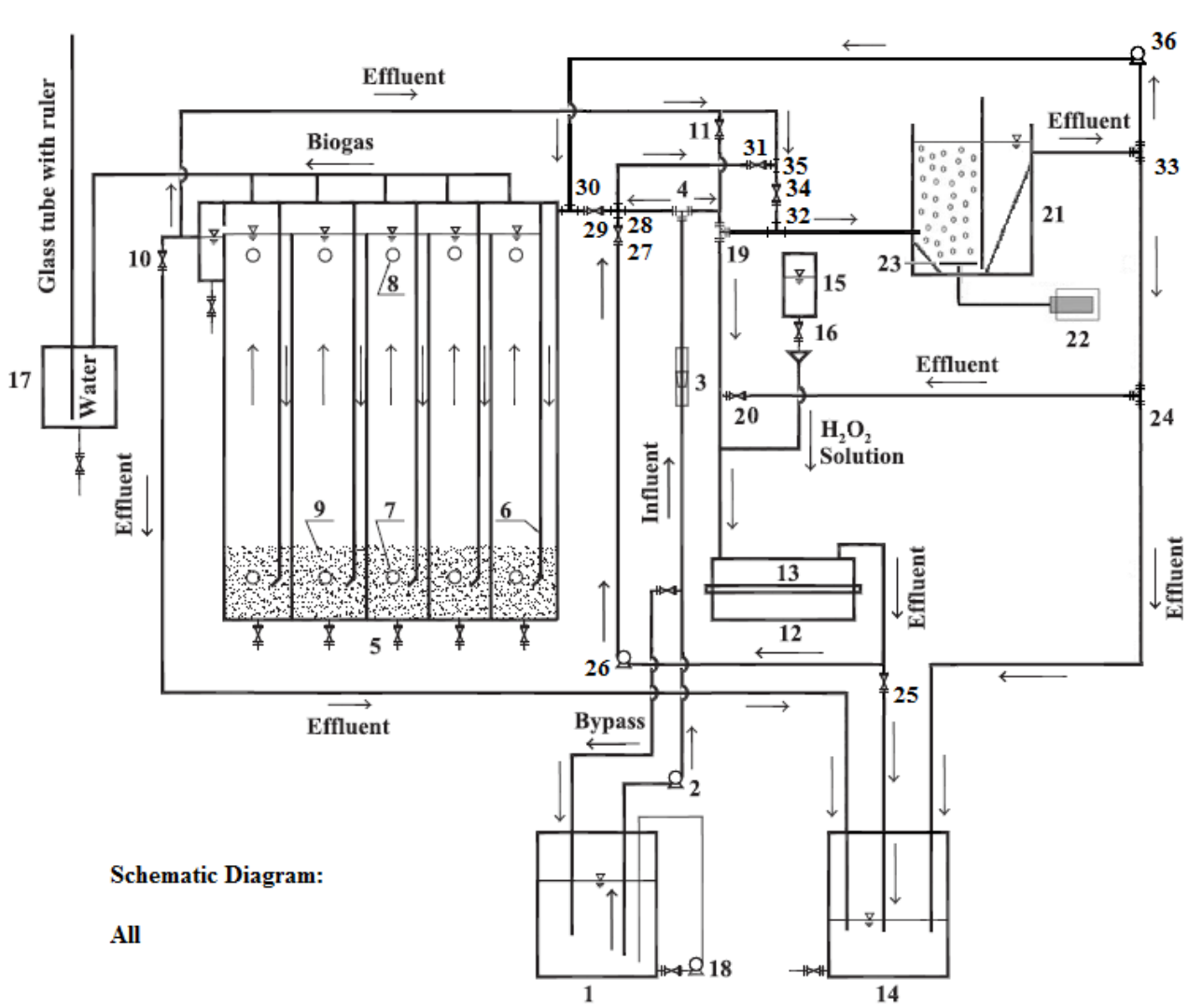
In order to optimize the combined ABR and UV/H_2O_2 process for wastewater treatment in previous studies (Cao, 2009; Cao and Mehrvar, 2011), it was proposed that an aerobic stage be located after the anaerobic process and before the post-treatment by UV/H_2O_2 as shown in Figures 3.3 and 3.4. An aerobic reactor was proposed to operate at a constant flow rate of 10.51 mL/min under HRT of 7 days. The aerobic reactor had an effective volume of 12 L. For the easy build-up of nitrifying bacteria in the bioreactor, no sludge should be discharged and a DO concentration must be maintained over 2.0 mg/L. The internal recycle ratio was recommended to be in the range of 100–300% of influent flow rate for the denitrification of oxidized nitrogen as suggested by Ahn et al. (2007). Different configurations were also designed in order to observe the performance of the system by varying the number of stages and their order, and thus determine the most effective alternative for the treatment of slaughterhouse wastewater by means of a cost-effective method as shown in Figures 3.5 to 3.10; where, the blue color indicates the flow direction of wastewater, the red color indicates the anaerobic process, the green color indicates the aerobic process, and the purple color indicates the photochemical process.

3.4. Experimental procedure

3.4.1. Acclimatization of the inoculum

The ABR was filled with 10 L of an anaerobic sludge seed (37,500 mgSS/L), using 2 L of the inoculum for each of the 5 compartments, approximately 1/3 of the total working volume of each compartment; whereas, 5 L of an aerobic sludge seed was loaded into the aerobic AS reactor. The inoculum (2.5 gVSS/L) was acclimatized by feeding the SSWW continuously into the reactors at a constant flow rate of 5.25 mL/min. During the 60-day acclimatization, the influent concentration was gradually increased from 20, 40, 60, and 80 to 100% of the raw SSWW, and then the system was inoculated with 10 – 20 gVSS/L. The concentration of SSWW was increased from 20 to 40%, from 40 to 60%, from 60 to 80%, and from 80 to 100% on the 16^{th}, 24^{th}, 30^{th}, and 42^{nd} day, respectively.

Samples were collected from every compartment during the acclimatization to measure their TSS and VSS concentrations. These parameters were used to observe the growth of microorganisms and to confirm the acclimatization process. On the other hand, if any washout was observed in the effluent of the reactors, the sludge should be removed in order to prevent an increase of TSS in the wastewater, which can result in a reduction of the efficiency and will require further post-treatment.



1) Wastewater feed tank
2) Peristaltic pump
3) Flow meter
4) 3-way valve
5) Anaerobic baffled reactor
6) Slanted edge baffle
7) Sludge sampling valve
8) Wastewater sampling valve
9) Anaerobic Sludge
10) 2-way valve
11) 2-way valve
12) UV photoreactor
13) UV lamp
14) Treated wastewater collection tank
15) H_2O_2 solution container
16) Flowrate control valve
17) Gas collection container
18) Recirculating pump
19) 3-way valve
20) 2-way valve
21) Aerobic reactor
22) Air blower
23) Diffuser
24) 3-way valve
25) 2-way valve
26) Peristaltic pump
27) 2-way valve
28) Cross-section piping
29) 2-way valve
30) Tee-section piping
31) 2-way valve
32) Tee-section piping
33) 3-way valve
34) 2-way valve
35) Tee-section piping
36) Peristaltic pump

Figure 3.3. Schematic diagram of the experimental set up for the treatment of synthetic slaughterhouse wastewater by combined anaerobic-aerobic and UV/H_2O_2 processes.

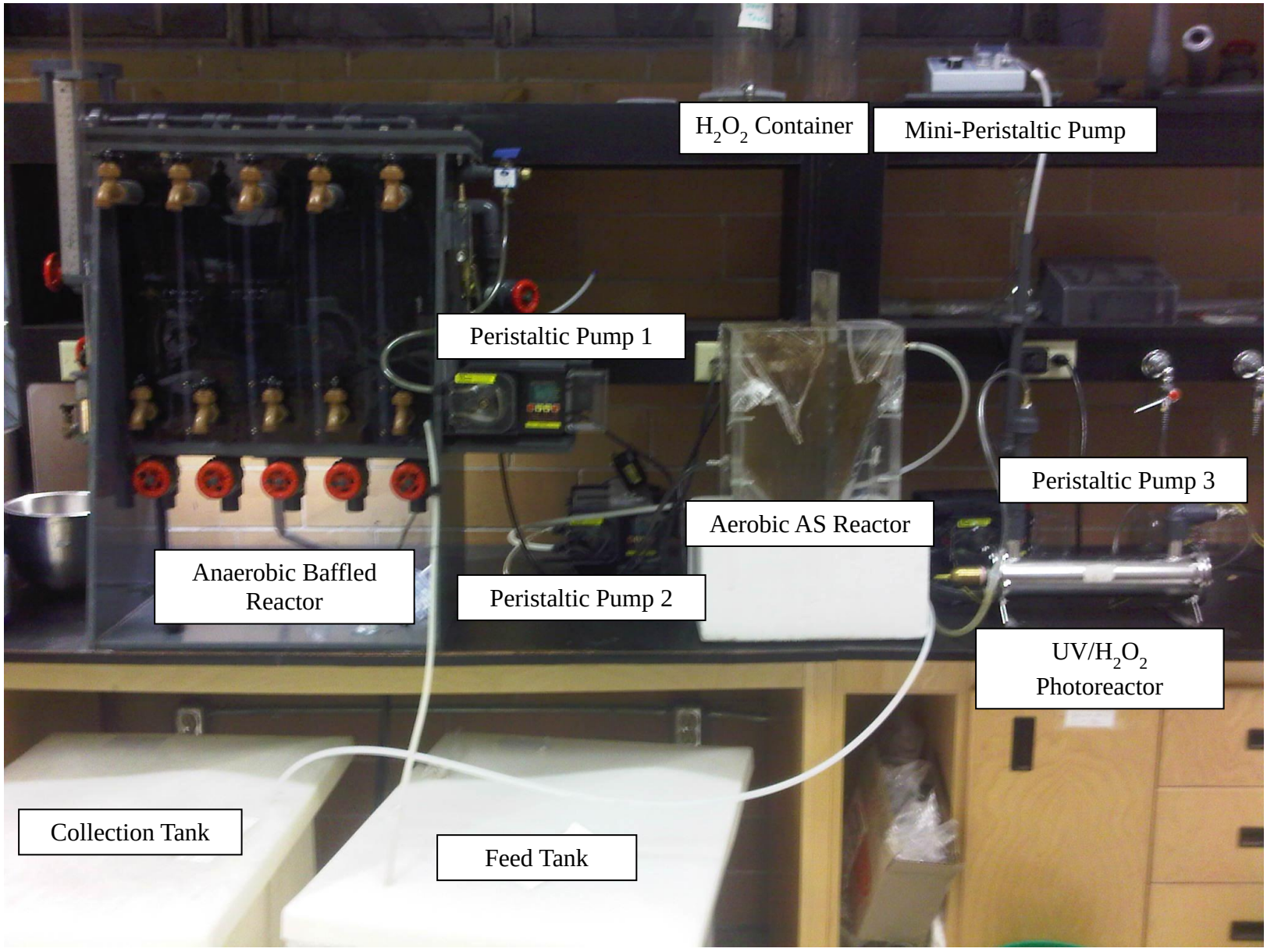


Figure 3.4. Laboratory view of the experimental setup.

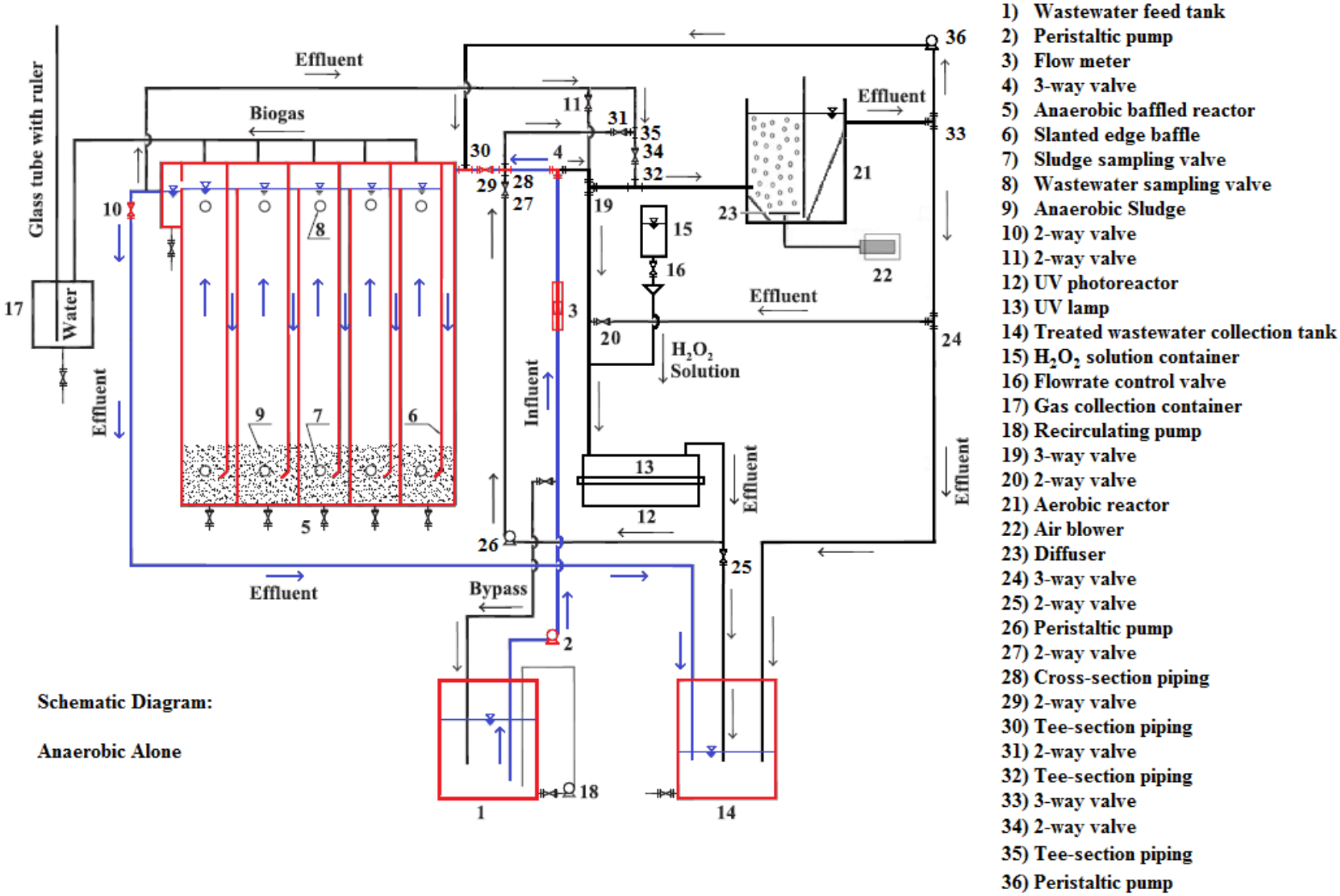
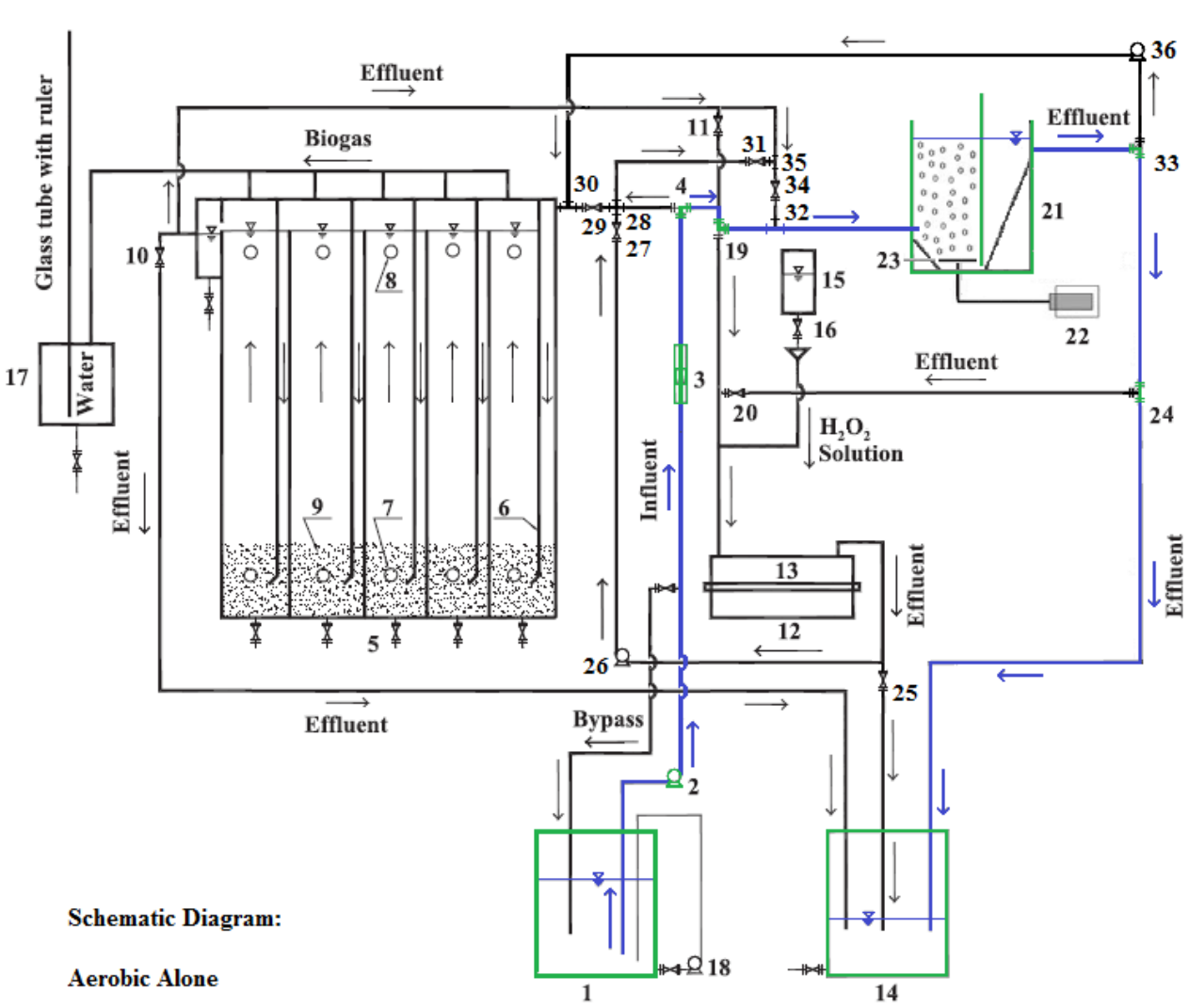
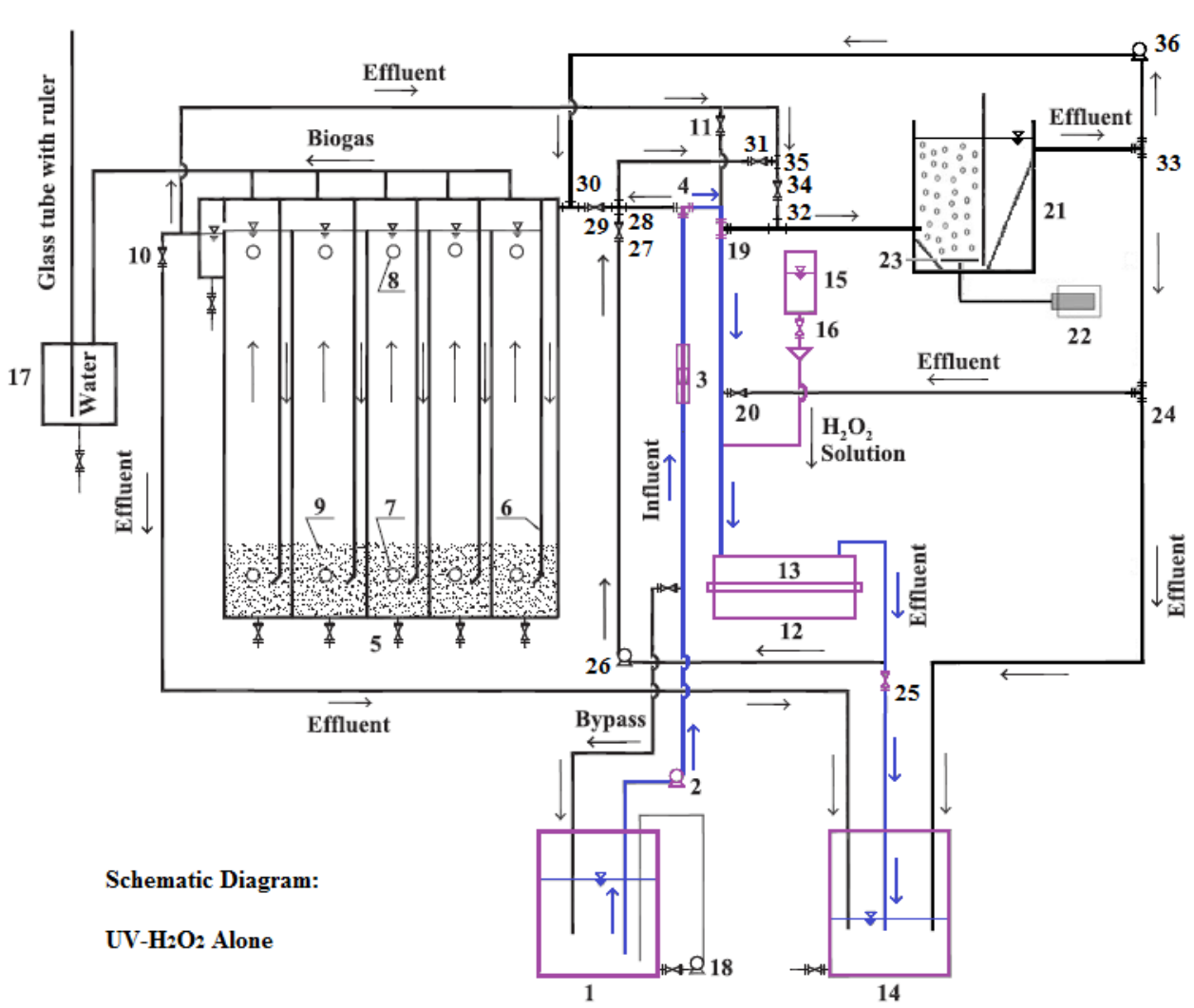


Figure 3.5. Schematic diagram of the experimental set up for the treatment of synthetic slaughterhouse wastewater by anaerobic process alone. The blue color indicates the flow direction of wastewater.



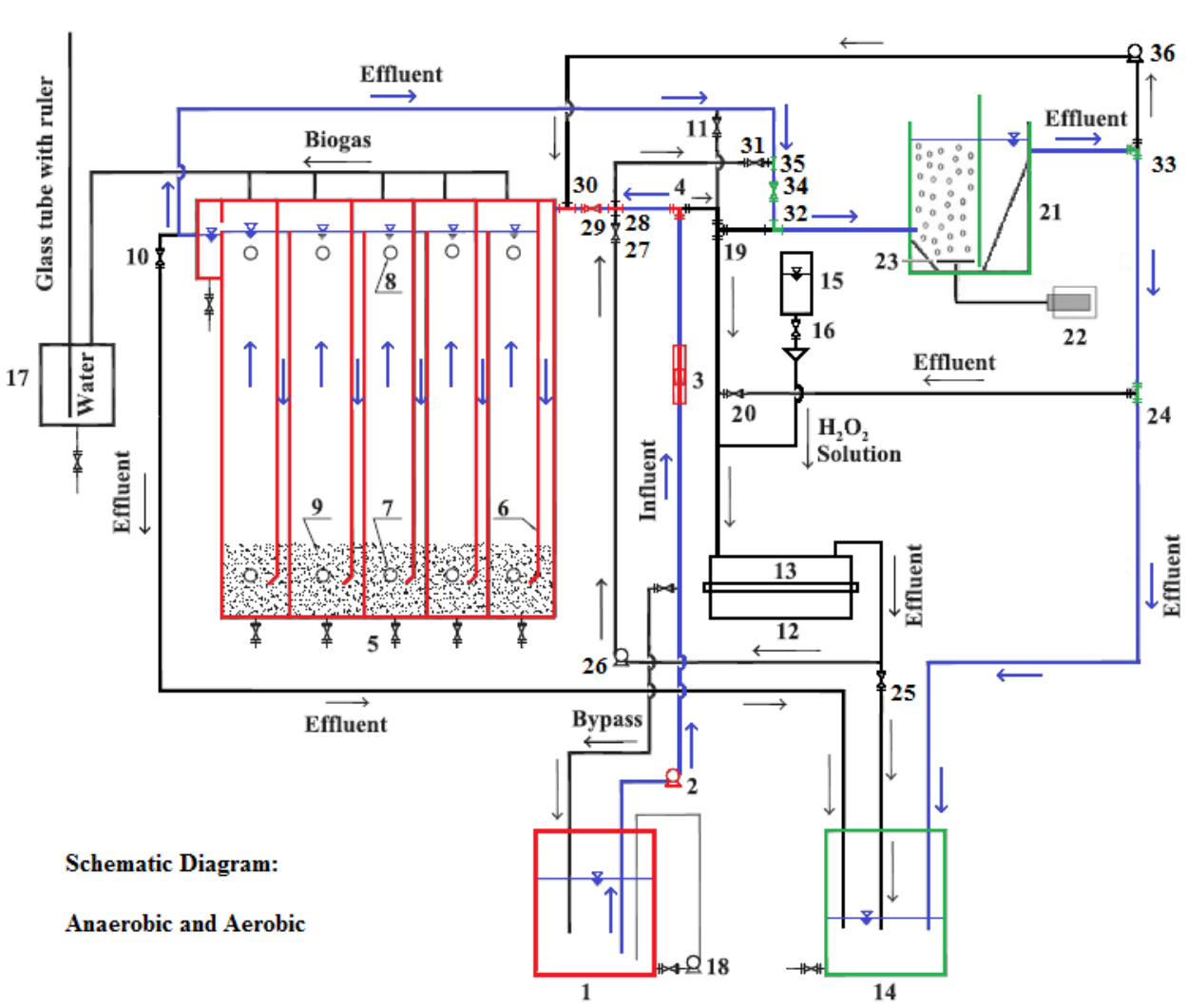
1) Wastewater feed tank
2) Peristaltic pump
3) Flow meter
4) 3-way valve
5) Anaerobic baffled reactor
6) Slanted edge baffle
7) Sludge sampling valve
8) Wastewater sampling valve
9) Anaerobic Sludge
10) 2-way valve
11) 2-way valve
12) UV photoreactor
13) UV lamp
14) Treated wastewater collection tank
15) H_2O_2 solution container
16) Flowrate control valve
17) Gas collection container
18) Recirculating pump
19) 3-way valve
20) 2-way valve
21) Aerobic reactor
22) Air blower
23) Diffuser
24) 3-way valve
25) 2-way valve
26) Peristaltic pump
27) 2-way valve
28) Cross-section piping
29) 2-way valve
30) Tee-section piping
31) 2-way valve
32) Tee-section piping
33) 3-way valve
34) 2-way valve
35) Tee-section piping
36) Peristaltic pump

Figure 3.6. Schematic diagram of the experimental set up for the treatment of synthetic slaughterhouse wastewater by aerobic process alone. The blue color indicates the flow direction of wastewater.



1) Wastewater feed tank
2) Peristaltic pump
3) Flow meter
4) 3-way valve
5) Anaerobic baffled reactor
6) Slanted edge baffle
7) Sludge sampling valve
8) Wastewater sampling valve
9) Anaerobic Sludge
10) 2-way valve
11) 2-way valve
12) UV photoreactor
13) UV lamp
14) Treated wastewater collection tank
15) H_2O_2 solution container
16) Flowrate control valve
17) Gas collection container
18) Recirculating pump
19) 3-way valve
20) 2-way valve
21) Aerobic reactor
22) Air blower
23) Diffuser
24) 3-way valve
25) 2-way valve
26) Peristaltic pump
27) 2-way valve
28) Cross-section piping
29) 2-way valve
30) Tee-section piping
31) 2-way valve
32) Tee-section piping
33) 3-way valve
34) 2-way valve
35) Tee-section piping
36) Peristaltic pump

Figure 3.7. Schematic diagram of the experimental set up for the treatment of synthetic slaughterhouse wastewater by UV/H_2O_2 process alone. The blue color indicates the flow direction of wastewater.



1) Wastewater feed tank
2) Peristaltic pump
3) Flow meter
4) 3-way valve
5) Anaerobic baffled reactor
6) Slanted edge baffle
7) Sludge sampling valve
8) Wastewater sampling valve
9) Anaerobic Sludge
10) 2-way valve
11) 2-way valve
12) UV photoreactor
13) UV lamp
14) Treated wastewater collection tank
15) H_2O_2 solution container
16) Flowrate control valve
17) Gas collection container
18) Recirculating pump
19) 3-way valve
20) 2-way valve
21) Aerobic reactor
22) Air blower
23) Diffuser
24) 3-way valve
25) 2-way valve
26) Peristaltic pump
27) 2-way valve
28) Cross-section piping
29) 2-way valve
30) Tee-section piping
31) 2-way valve
32) Tee-section piping
33) 3-way valve
34) 2-way valve
35) Tee-section piping
36) Peristaltic pump

Figure 3.8. Schematic diagram of the experimental set up for the treatment of synthetic slaughterhouse wastewater by combined anaerobic-aerobic processes. The blue color indicates the flow direction of wastewater.

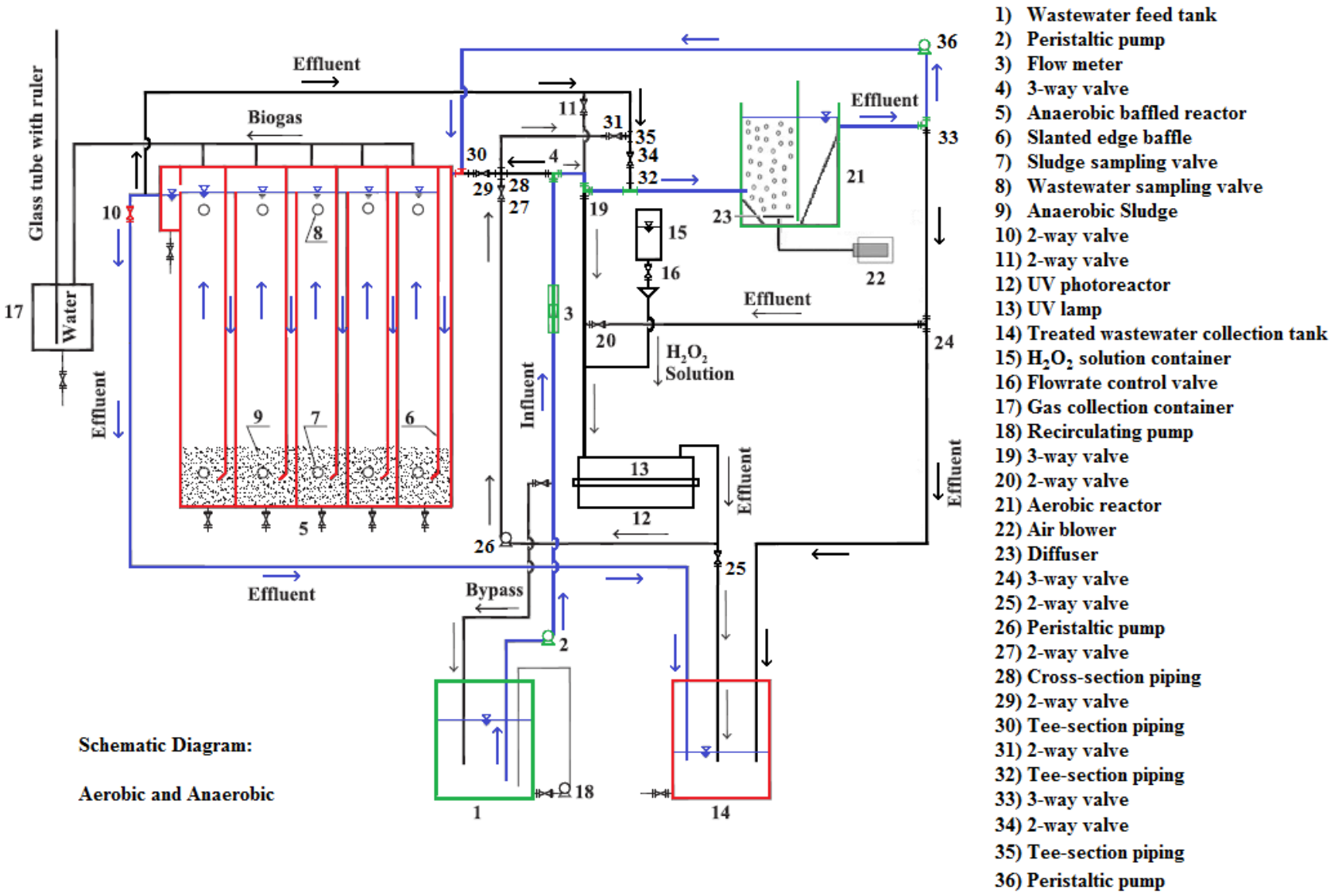
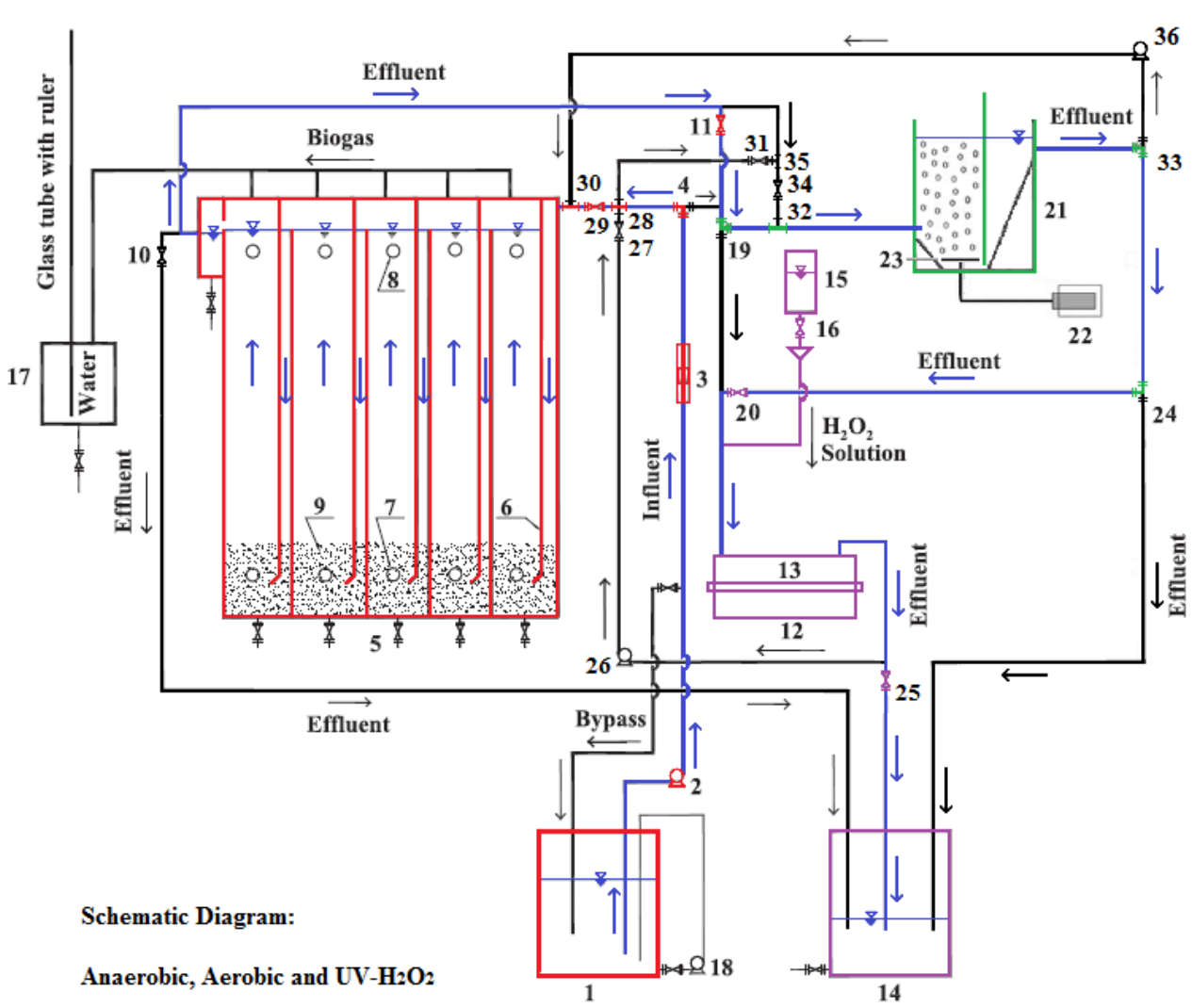


Figure 3.9. Schematic diagram of the experimental set up for the treatment of synthetic slaughterhouse wastewater by combined aerobic-anaerobic processes. The blue color indicates the flow direction of wastewater.



1) Wastewater feed tank
2) Peristaltic pump
3) Flow meter
4) 3-way valve
5) Anaerobic baffled reactor
6) Slanted edge baffle
7) Sludge sampling valve
8) Wastewater sampling valve
9) Anaerobic Sludge
10) 2-way valve
11) 2-way valve
12) UV photoreactor
13) UV lamp
14) Treated wastewater collection tank
15) H_2O_2 solution container
16) Flowrate control valve
17) Gas collection container
18) Recirculating pump
19) 3-way valve
20) 2-way valve
21) Aerobic reactor
22) Air blower
23) Diffuser
24) 3-way valve
25) 2-way valve
26) Peristaltic pump
27) 2-way valve
28) Cross-section piping
29) 2-way valve
30) Tee-section piping
31) 2-way valve
32) Tee-section piping
33) 3-way valve
34) 2-way valve
35) Tee-section piping
36) Peristaltic pump

Figure 3.10. Schematic diagram of the experimental set up for the treatment of synthetic slaughterhouse wastewater by combined anaerobic-aerobic and UV/H_2O_2 processes. The blue color indicates the flow direction of wastewater.

3.4.2. ABR process

After 60 days of acclimatization period, the ABR was run alone (Figure 3.5) using 5 different influent concentrations of the SSWW at various flow rates in the range of 2.93 to 11.70 mL/min, HRT of 2 to 8 days, TOC loading rates of 0.03–1.01 g/(L.day), and TN loading rates of 0.01–0.19 g/(L.day).

As shown in Figure 3.5, the SSWW was homogenized by a recirculating pump (18). The ABR (5) was fed continuously from a feed tank (1) using the peristaltic pump (Blue-White Industries Ltd. Flexflo A-100NV) (2). The SSWW was passed through an acrylic flow meter (Omega FL-2018) (3) in order to measure the flow rate. The flow was then directed to the ABR using the 3-way valve (4) and flowed downwards and upwards within the five compartments of the ABR. Those compartments contained an anaerobic sludge layer (9) where the biological degradation occurs. Each compartment had a sludge sampling port (7), 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. SSWW sampling ports (8) were located 40 cm from the base of the ABR and 4 cm from the side of the 45° slanted edge baffle. SSWW treated in the ABR was either discharged into a collection tank (14) or flowed into another reactor for post-treatment by means of the 3-way valve (10).

SSWW samples were taken by gravity from every compartment. When collecting samples, the first 10 mL were eliminated to avoid the effect of the sampling ports; then, volumes of 30 mL were collected from each SSWW sampling port and were diluted to reach 1/3 of their concentrations in order to measure temperature, pH, DO, TOC, TN, $CBOD_5$, TSS, and VSS. Sludge samples were also collected from the sludge sampling ports in order to measure TSS and VSS.

3.4.3. Aerobic AS process

The aerobic AS process was run alone (Figure 3.6) using five different influent concentrations of the SSWW at various flow rates in the range of 2.93 to 11.70 mL/min, HRT of 2 to 8 days, TOC loading rates of 0.03–1.01 g/(L.day), and TN loading rates of 0.01–0.19 g/(L.day). As shown in Figure 3.6, the SSWW was homogenized by a recirculating pump (18). The aerobic AS reactor (21) was fed continuously from a feed tank (1) using the peristaltic pump (2). The SSWW was passed through an acrylic flow meter (3). The flow was directed to the aerobic AS reactor using the 3-way

valve (4) and flowed into the aeration tank, where oxygen was introduced by a diffuser at a constant flow rate of 500 mL/min (23) followed by a clarifier. The SSWW treated in the aerobic AS reactor was either discharged into a collection tank (14) or flowed into another reactor for post-treatment due by means of the 2-way valves (33) and (24).

SSWW samples were taken from the aeration tank and the clarifier. Volumes of 30 mL were collected from each stage and diluted to reach 1/3 of their concentrations in order to measure temperature, pH, DO, TOC, TN, $CBOD_5$, TSS, and VSS.

3.4.3. UV/H_2O_2 process

The UV/H_2O_2 process was run alone (Figure 3.7), using 3 different influent concentrations (5, 10 and 25%) of the SSWW at various flow rates in the range of 2.93 to 11.70 mL/min, HRT in the range from 30 to 180 min, TOC concentrations of 57.59–140.91 mg/L, and H_2O_2 concentrations of 0, 100, 300, 600, 900, 1200, 1500 and 2000 mg/L.

As shown in Figure 3.7, the SSWW was homogenized by a recirculating pump (18). The UV photoreactor (12) was fed continuously from a feed tank (1) using the peristaltic pump (2). The SSWW was passed through an acrylic flow meter (3). The flow was directed to the UV photoreactor using the 3-way valve (4) and flowed into the UV photoreactor, where H_2O_2 was introduced from a H_2O_2 solution container (15) using a flow rate control valve (16). The SSWW treated in the UV photoreactor was either discharged into a collection tank (14) or flowed into another reactor for post-treatment due to the 2-way valve (25).

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 using H_2O_2 concentrations of 0, 600, and 1200 mg/L. SSWW samples were taken from the UV photoreactor effluent. Volumes of 30 mL were collected from each stage and were diluted to reach 1/3 of its concentrations and to measure temperature, pH, DO, TOC, TN, and $CBOD_5$. Two replicates were made for every analytical measurement. Catalase was required to eliminate H_2O_2 from the samples during $CBOD_5$ measurement for accurate results. It catalyzes the decomposition of H_2O_2 to water and oxygen as expressed in Section 2.3.7. Experiments using a batch recirculation mode (Figure 3.11) were also conducted in order to evaluate the optimum H_2O_2 dosage and the molar ratio of

[H_2O_2]/[TOC]. Different inlet concentrations of H_2O_2 (0, 100, 300, 600, 900, 1200, 1500, and 2000 mg/L), SSWW (64.88, 163.69, and 349.84 mgTOC/L), and HRT (30, 60, 90, 120, 150, and 180 min) were studied.

3.4.4. Combined anaerobic-aerobic processes

Combined processes of the ABR and the aerobic AS (Figure 3.8) were run using various flow rates of 3.75 to 7.50 mL/min, HRT of 3.12 to 6.24 days, TOC loading rates of 0.16–0.32g/(L.day), and TN loading rates of 0.07–0.14 g/(L.day). As shown in Figure 3.8, the SSWW was homogenized by a recirculating pump (18). The ABR (5) was fed continuously from a feed tank (1) using the peristaltic pump (2). The SSWW was passed through an acrylic flow meter (3). The flow was then directed to the ABR using the 3-way valve (4) and flowed downwards and upwards within the 5 compartments of the ABR. Those compartments contained an anaerobic sludge layer (9) where the biological degradation occurs. Each compartment had a sludge sampling port (7), 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 SSWW sampling ports (8) were located 40 cm from the base of the ABR and 4 cm from the side of the 45° slanted edge baffle. The treated SSWW in the ABR was flowed into the aerobic AS reactor for post-treatment using a 3-way valve (10) and flowed into the aeration tank, where oxygen was introduced by a diffuser at a constant flow rate of 500 mL/min (23) followed by a clarifier. The treated SSWW was then discharged into a collection tank (14). SSWW samples were taken similarly to the previous processes. In addition, an experiment was conducted with recycling mode, in which the SSWW treated in the aerobic AS reactor was recycled into the ABR using the 2-way valve (33).

3.4.5. Combined aerobic-anaerobic processes

Experiments for the aerobic AS and ABR combined processes (Figure 3.9) were conducted using similar operating conditions as other processes. As shown in Figure 3.9, the SSWW was homogenized by a recirculating pump (18). The ABR (5) was fed continuously from a feed tank (1) using the peristaltic pump (2). The SSWW was passed through an acrylic flow meter (3). The flow was then directed to the aerobic AS reactor using the 3-way valve (4) and flowed into the aeration tank, where oxygen was introduced by a diffuser at a constant flow rate of 500 mL/min (23) followed by a clarifier. The treated SSWW was then directed into the ABR for post-treatment using the 3-way valve (33) and flowed downwards and upwards within the compartments of the ABR.

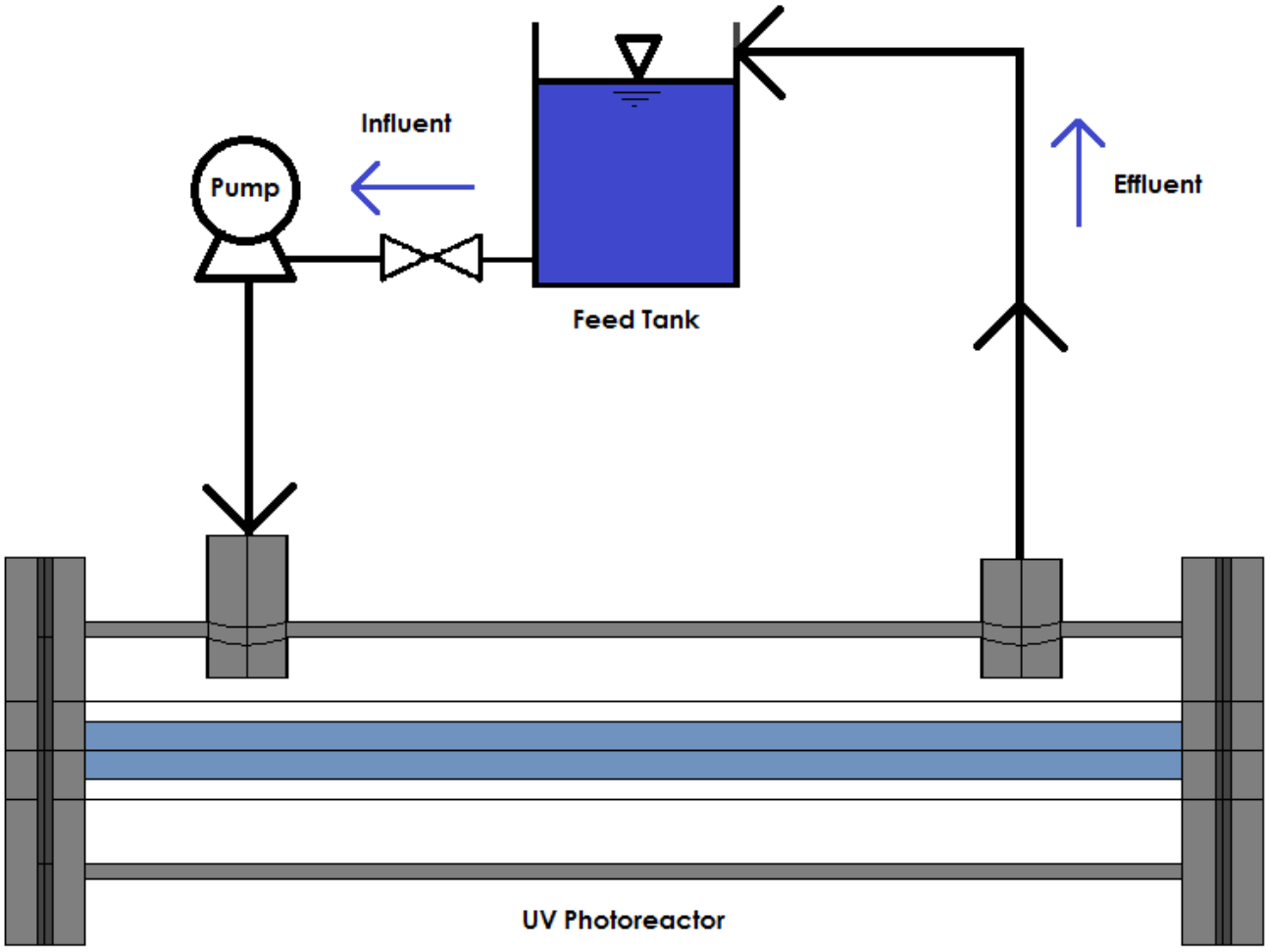


Figure 3.11. Experimental setup of the batch recirculation UV/H_2O_2 process.

Those compartments contained an anaerobic sludge layer (9) where the biological degradation occurs and each compartment had a sludge sampling port (7), 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. SSWW sampling ports (8) were located 40 cm from the base of the ABR and 4 cm from the side of the 45° slanted edge baffle. The treated SSWW was discharged into a collection tank (14). SSWW samples were taken similarly to the previous processes.

3.4.6. Combined anaerobic-aerobic and UV/H_2O_2 processes

Experiments for combined processes of the ABR, the aerobic AS, and UV/H_2O_2 (Figure 3.10) were conducted at various flow rates of 5.90 to 7.50 mL/min, HRT of 3.15 to 4.00 days, TOC of 941.19–1,006.90 mg/L, and TN of 200.03–214.08 mg/L.

As shown in Figure 3.10, the SSWW was homogenized by a recirculating pump (18). The ABR (5) was fed continuously from a feed tank (1) using the peristaltic pump (2). The SSWW was passed through an acrylic flow meter (3) in order to measure the flow rate. The flow was then directed to the ABR using the 3-way valve (4) and flowed downwards and upwards within the compartments of the ABR. Those compartments contained an anaerobic sludge layer (9) where the biological degradation occurs. Each compartment had a sludge sampling port (7), 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. SSWW sampling ports (8) were located 40 cm from the base of the ABR and 4 cm from the side of the 45° slanted edge baffle. The treated SSWW in the ABR flowed into the aerobic AS reactor for post-treatment by means of the 3-way valve (10) and flowed into the aeration tank, where oxygen was introduced by a diffuser at a constant flow rate of 500 mL/min (23) followed by a clarifier. The treated SSWW was directed to the UV photoreactor using the 3-way valve (24) and flowed into the UV photoreactor, where H_2O_2 was introduced from a H_2O_2 solution container (15) using a flow rate control valve (16). SSWW treated in the UV photoreactor was discharged into a collection tank (14). SSWW samples were taken similarly to the previous processes.

In combined processes, there is a relationship between the HRT and the volume of each reactor. Considering the flow rate of the H_2O_2 negligible, this relationship can be represented by Equation (3.1).

$$\frac{V_{ABR}}{HRT_{ABR}} = \frac{V_{AS}}{HRT_{AS}} = \frac{V_{UV}}{HRT_{UV}} \quad (3.1)$$

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);

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

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

HRT_{UV} = hydraulic retention time of the UV/H_2O_2 process (h).

3.5. Analytical techniques

Different parameters of the SSWW were measured, including temperature, pH, DO, TSS, VSS, TOC, TN, and $CBOD_5$ according to the *Standard Methods* (APHA, 1998). The details of each analytical technique are explained in the following sections.

3.5.1. Dissolved oxygen (DO)

DO of influent and effluent samples of the SSWW was measured by a dissolved oxygen meter (YSI 58 Dissolved Oxygen Meter) equipped with a BOD bottle probe (YSI 5905 BOD Probe), where the DO was displayed in mg/L (1 mg/L = 1 ppm) or in percent air saturation. 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.

3.5.2. Temperature and pH

Temperature and pH of influent and effluent samples of the slaughterhouse wastewater were measured by a portable pH and pH/ISE meter (Thermo Orion 230A+). 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 ±1.0°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.

3.5.3. Total suspended solids (TSS), volatile suspended solids (VSS), mixed liquor suspended solids (MLSS), and mixed liquor volatile suspended solids (MLVSS)

TSS and VSS of the anaerobic sludge, MLSS and MLVSS of the aerobic sludge, and the SSWW effluent of each reactor were measured according to sections 2540D and 2540E of *Standard Methods* (APHA, 1998) to observe the growth of microorganisms in the reactors or to assess whether the effluent solids concentrations reached a disposal level as shown in Table 2.8.

For TSS and MLSS, filter papers and aluminum weighing dishes were dried in an oven (Binder Oven FED 53) at 105°C for 1 h. 5 to 10 mL of well-mixed sludge samples 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. The TSS and the MLSS could be determined by Equation (3.2).

$$TSS = \frac{(W_1 - W_2 - W_3)}{V} \tag{3.2}$$

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 and the MLVSS 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. VSS and MLVSS could be determined by Equation (3.3), where W_4 is the sum of the weights of the solids of the sample and the dish after burning (mg).

$$VSS = \frac{(W_1 - W_2 - W_3) - (W_4 - W_3)}{V} = TSS - \frac{(W_4 - W_3)}{V} \tag{3.3}$$

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

TOC and TN were measured by a Teledyne Tekmar Apollo 9000 Combustion TOC/TN Analyzer equipped with an automated sampler. Before sample analyses, the TOC/TN analyzer was calibrated, samples were diluted to reach 1/3 of their concentration, and they 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 nitrate (KNO_3) was used as a nitrogen source for TN calibration. The KNO_3 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 (Figure 3.12).
2. 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 (Figure 3.13). Thus, TOC removal efficiency was determined by Equation (3.4).

$$TOC = \frac{(TOC_{in} - TOC_{out})}{TOC_{in}} \cdot 100\% \quad (3.4)$$

where,

TOC_{in} = TOC concentration of influent wastewater sample (mg/L); and

TOC_{out} = TOC concentration of effluent wastewater sample (mg/L).

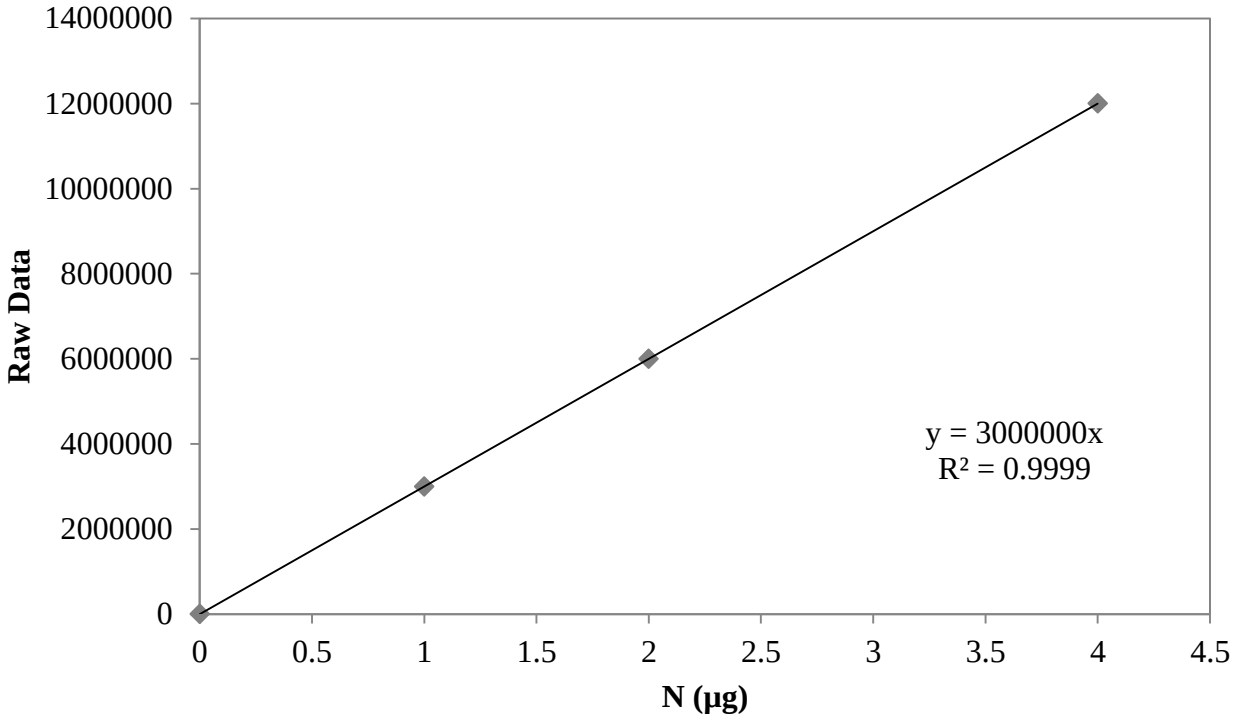


Figure 3.12. TN calibration curve for the range of 1–20 mgTN/L.

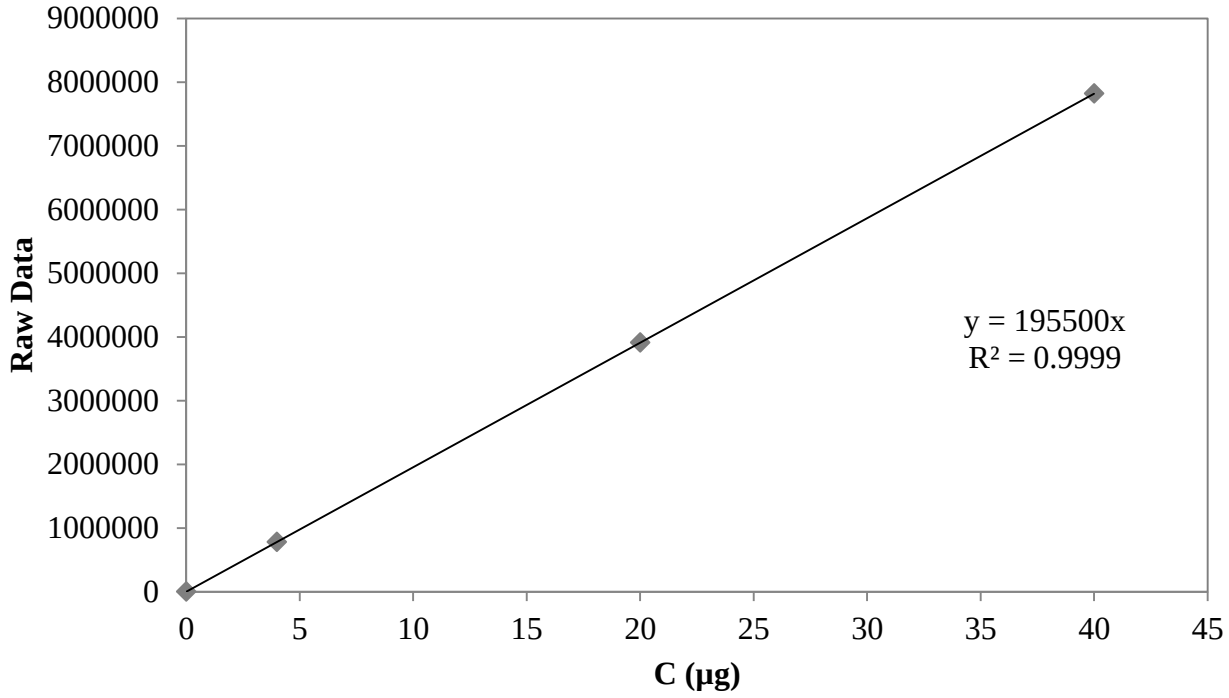


Figure 3.13. TOC calibration curve for the range of 1–400 mgTOC/L.

3.5.5. 5-day carbonaceous biochemical oxygen demand ($CBOD_5$)

The analysis of the $CBOD_5$ was carried out according to Section 5210B of *Standard Methods* (APHA, 1998). A solution, which is called a dilution solution in *Standard Methods 5210B*, contains the reagents of phosphate buffer solution, magnesium sulphate solution, calcium chloride solution, and ferric chloride solution. Other reagents used for $CBOD_5$ testing include acid and alkali solutions, nitrification inhibitor, and glucose-glutamic acid solution. All solutions, including phosphate buffer, magnesium sulphate, calcium chloride, and ferric chloride were prepared as follows and stored in a refrigerator at 4°C after preparation. Phosphate buffer: 8.5 g KH_2PO_4, 21.75 g K_2HPO_4, 33.4 g $Na_2HPO_4 \bullet 7H_2O$, and 1.7 g NH_4Cl were dissolved in 500 mL of distilled water and diluted to 1 L. The pH was adjusted to 7.2 using 1 N sulphuric acid or 1 N sodium hydroxide solution. Magnesium sulphate heptahydrate solution (22.5 g $MgSO_4 \cdot 7H_2O$) was dissolved in distilled water and diluted to 1 L. Calcium chloride solution (27.5 g $CaCl_2$) was dissolved in distilled water and diluted to 1 L. Ferric chloride solution (0.25 g $FeC1_3 \bullet 6H_2O$) was dissolved in distilled water and diluted to 1 L. 0.16 g of nitrification inhibitor (2-chloro-6-trichloromethyl pyridine; Hach Co., Formula 2533) was added to each BOD bottle.

For the glucose-glutamic acid (GGA) solution, reagent grade glucose and reagent grade glutamic acid were dried at 103°C for 1 h. 150 mg glucose and 150 mg glutamic acid were dissolved in distilled water and diluted to 1 L. Because the BOD test is a bioassay, its results may be greatly influenced by the presence of toxicants when using of a poor seeding material. Distilled waters frequently are contaminated with copper. Therefore, it is necessary to check dilution water quality, seed effectiveness, and analytical techniques periodically. Glucose-glutamic acid standard (GGA) was used to achieve this work. The GGA solution was prepared fresh immediately before use. For the dilution water, ten liters of solution were prepared each time as follows: 1 mL of each phosphate buffer, magnesium sulphate, calcium chloride, and ferric chloride per liter of distilled water were added in a 20 L container. Then, dilution water was placed in an incubator for at least 24 h at 20°C and was aerated by oxygen or pure air for 1 h before use. One capsule of commercial Polyseed® was added into 500 mL distilled water to prepare Polyseed® solution, which must be aerated by pure air for 30 min and then settled for 15 min before use. Three to 6 mL of one sample of the SSWW, 2 mL aerated Polyseed® solution, and 0.16 g nitrification inhibitor were added into one well-cleaned 300 mL BOD bottle.

Two blanks were prepared by filling with aerated dilution water to check the quality of un-seeded dilution water and the cleanliness of the BOD bottles roughly. Three seed controls had to be prepared by adding 10, 15, and 20 mL of Polyseed® solution into separate 300 mL BOD bottles. Two GGA standards were prepared by adding 6 mL GGA solution and 4 mL aerated Polyseed® solution into each BOD bottle. A magnetic stirrer bar, which is used to stir the solution in the BOD bottle to make it homogenous during BODs measurement, was placed in each bottle and then all BOD bottles were filled with the aerated dilution water up to the middle of the bottle's neck.

Initial DOs of all samples including wastewater samples, the blanks, the seed controls, and the GGA standards were first measured by a BOD bottle probe connected to an YSI 58 DO meter with sample agitation before incubating. All BOD bottles were incubated in the incubator at 20°C for 5 days. The 5-day DOs of all samples were measured and their $CBOD_5$ calculated by Equations (3.5) and (3.6). *%CBOD*$_5$ removal efficiency was determined by Equation (3.7).

$$CBOD_5 = \frac{(DO_0 - DO_f) - SCF}{V/V_{BOD}} \tag{3.5}$$

$$SCF = (SC_1 - SC_2)f \tag{3.6}$$

$$\%CBOD_5 = \frac{(CBOD_{5,in} - CBOD_{5,out})}{CBOD_{5,in}} \cdot 100\% \tag{3.7}$$

where,

DO$_0$ = dissolved oxygen of the sample immediately taken after preparation (mg/L);

DO$_f$ = dissolved oxygen of the sample after 5 days of incubation at 20C (mg/L);

SCF = seed correction factor, mg/L;

SC$_1$ = dissolved oxygen of seed control before incubation (mg/L);

SC$_2$ = dissolved oxygen of seed control after incubation (mg/L);

f = ratio of the volume of Polyseed solution in glucose-glutamic acid (GGA);

V = volume of the sample (mL);

V$_{BOD}$ = volume of a BOD bottle (mL);

CBOD$_{5,in}$ = $CBOD_5$ concentration of influent wastewater sample (mg/L); and

CBOD$_{5,out}$ = $CBOD_5$ concentration of effluent wastewater sample (mg/L).

CHAPTER 4

RESULTS AND DISCUSSION

4.1. Introduction

This chapter presents the results of the experimental work, the characteristics of the SSWW, the performance and the treatment ability of the ABR, the aerobic AS, and the UV/H_2O_2 processes, as well as their combination in the removal of TOC, TN, and BOD from SSWW. This is followed by the discussion of the optimum H_2O_2 dosage and the molar ratio of [H_2O_2]/[TOC] for the UV/H_2O_2 process obtained under specific operating conditions discussed in the material and methods chapter, as well as a cost-effectiveness analysis to present the best alternative among the different configurations evaluated during this study.

4.2. Common characteristics of the synthetic slaughterhouse wastewater (SSWW)

General characteristics, which remained without significant changes, of the SSWW used during the experiments are shown in this section, including Reynolds number, temperature, pH, DO, TSS, and VSS.

4.2.1. Reynolds number

The Reynolds number for all the processes, including the ABR, the aerobic AS, the UV/H_2O_2, and their combination, remained lower than 2,000; thus, laminar flow was the common regime.

4.2.2. Dissolved oxygen (DO)

The DO concentration of the untreated SSWW remained in the range of 8.48 to 8.50 mg/L. In the enclosed feed tank, the DO concentration decreased to 0.5–1.3mg/L. After acclimatization, the DO values within each compartment (1 to 5) of the ABR were in the ranges of 0.2–1.1, 0.3–1.0, 0.4–1.2, 0.2–1.0, and 0.2–1.0 mg/L, respectively. Inside the aeration tank, DO values were in the range of 0.4–3.2 mg/L; and within the UV/H_2O_2, DO values were in the range of 1.4–4.1 mg/L. DO values in the reactors are illustrated in Figure 4.1; error bars represent standard deviations.

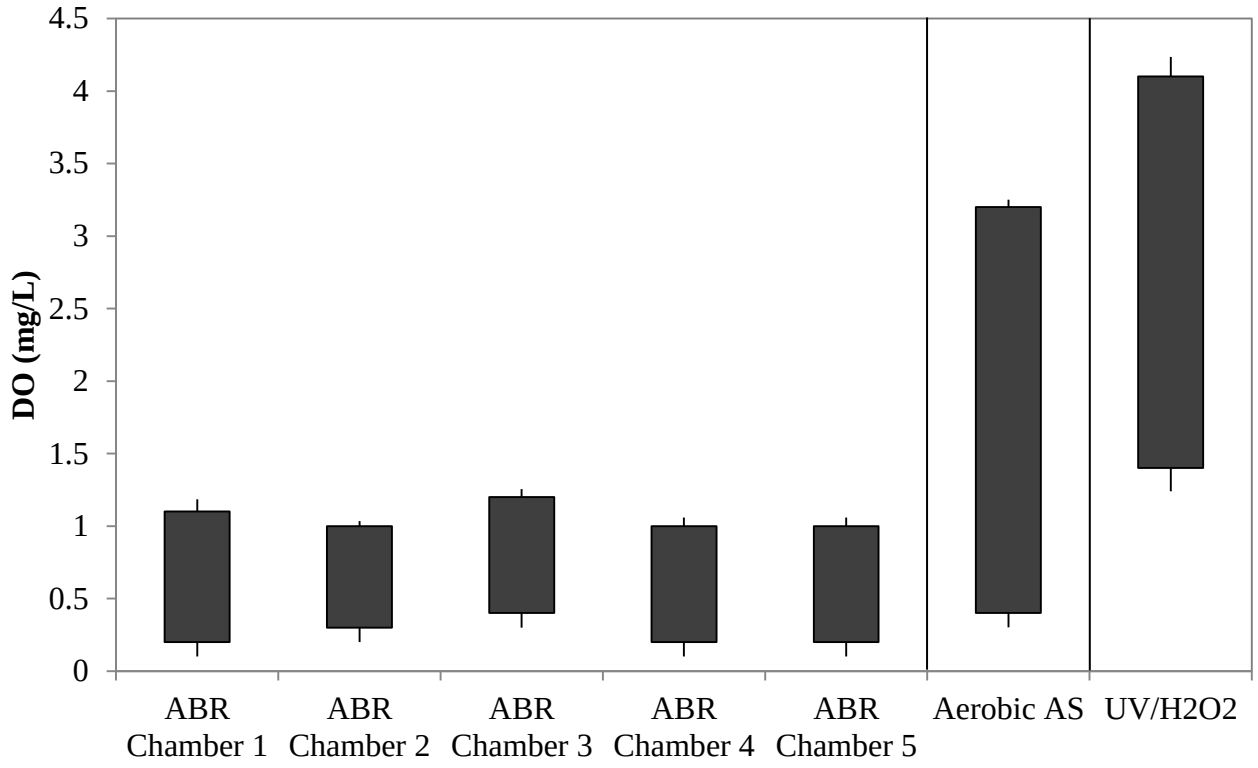


Figure 4.1. DO profile of the SSWW in the ABR chambers, aerobic AS and UV photoreactor. Error bars represent standard deviations.

4.2.3. Temperature and pH

Figure 4.2 shows the profile of the pH evolution of the SSWW in the ABR, aerobic AS, and UV/H_2O_2 reactors. The SSWW influent pH values were in the range of 6.82 to 6.92. During the acclimatization of the sludge, pH values for the biological reactors were fluctuating drastically. This may be attributed to the growth and metabolism of the microorganisms, where pH values within the ABR chambers (1 to 5) were in the ranges of 6.46–7.00, 6.05–6.97, 6.01–7.06, 6.52–7.21, 6.50–7.21, 5.78–7.85, and 6.18–6.20, respectively; and pH values in the aerobic AS aeration tank were in the range of 5.78–7.85.

In contrast, pH values during experiments within the 5 chambers of the ABR were in the ranges of 6.70–6.82, 6.51–6.57, 6.80–6.81, 6.79–6.81, and 6.91–6.95; likewise, pH values in the aeration tank were in the range of 6.92–6.97. Moreover, from the effluent of the UV/H_2O_2 process, pH values were in the range of 6.18 to 6.20. A summary of the maximum and minimum SSWW pH values is depicted in Table 4.1.

Table 4.1. Maximum and minimum of SSWW pH values during acclimatization of sludge and experiments.

	pH values during acclimatization		**pH values during experiments**	
Reactor	**Minimum**	**Maximum**	**Minimum**	**Maximum**
ABR Chamber 1	6.46	7.00	6.70	6.82
ABR Chamber 2	6.05	6.97	6.51	6.57
ABR Chamber 3	6.01	7.06	6.80	6.81
ABR Chamber 4	6.52	7.21	6.79	6.81
ABR Chamber 5	6.50	7.21	6.91	6.95
Aeration Tank	5.78	7.85	6.92	6.97
UV/H_2O_2	-	-	6.18	6.20

Figure 4.3 shows the profile of the SSWW temperature evolution in the ABR, aerobic AS, and UV/H_2O_2 reactors. The SSWW influent temperature values were in the range of 24.7 to 24.9°C. During the acclimatization of the sludge, temperature values for the biological reactors were fluctuating drastically. This may be attributed to the growth and metabolism of the microorganisms, where temperature values within the ABR chambers (1 to 5) were in the ranges of 24.0–25.5, 24.3–25.7, 24.1–25.6, 24.4–25.4, and 24.1–25.5°C, respectively. Temperature values in the aerobic AS aeration tank were in the range of 24.1–25.6°C.

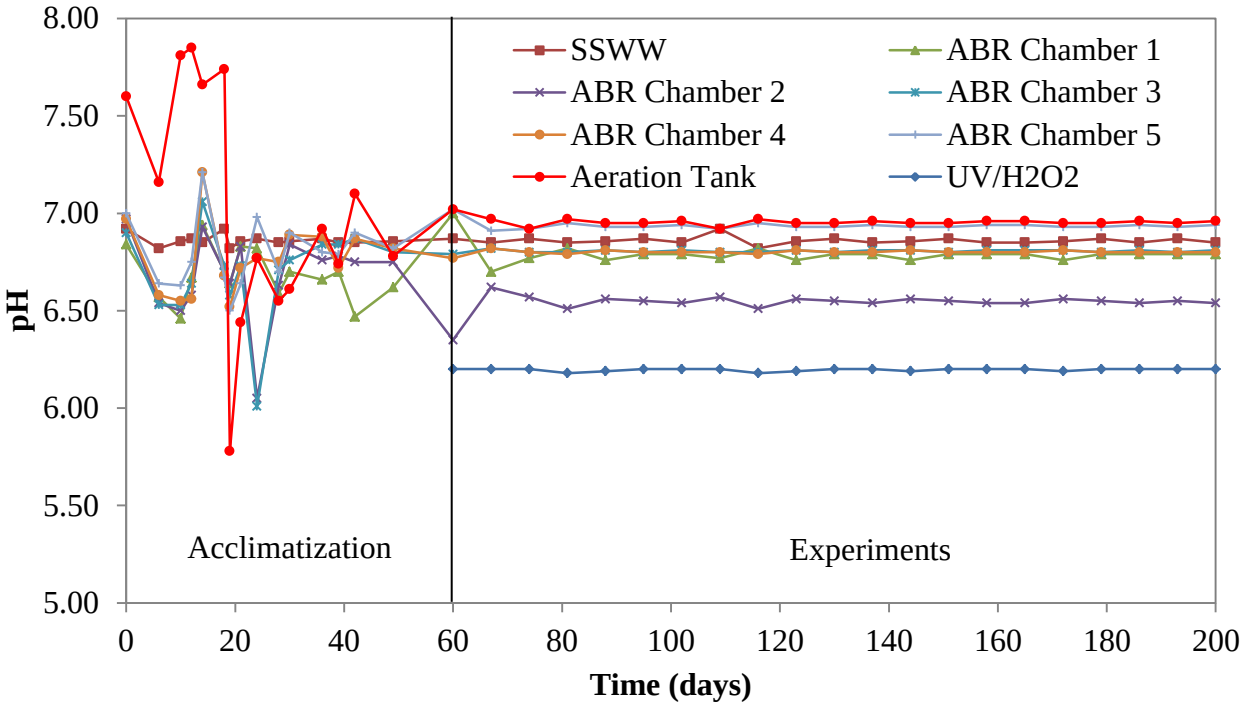


Figure 4.2. SSWW pH evolution with time in the ABR, the aerobic AS and UV/H_2O_2 reactors.

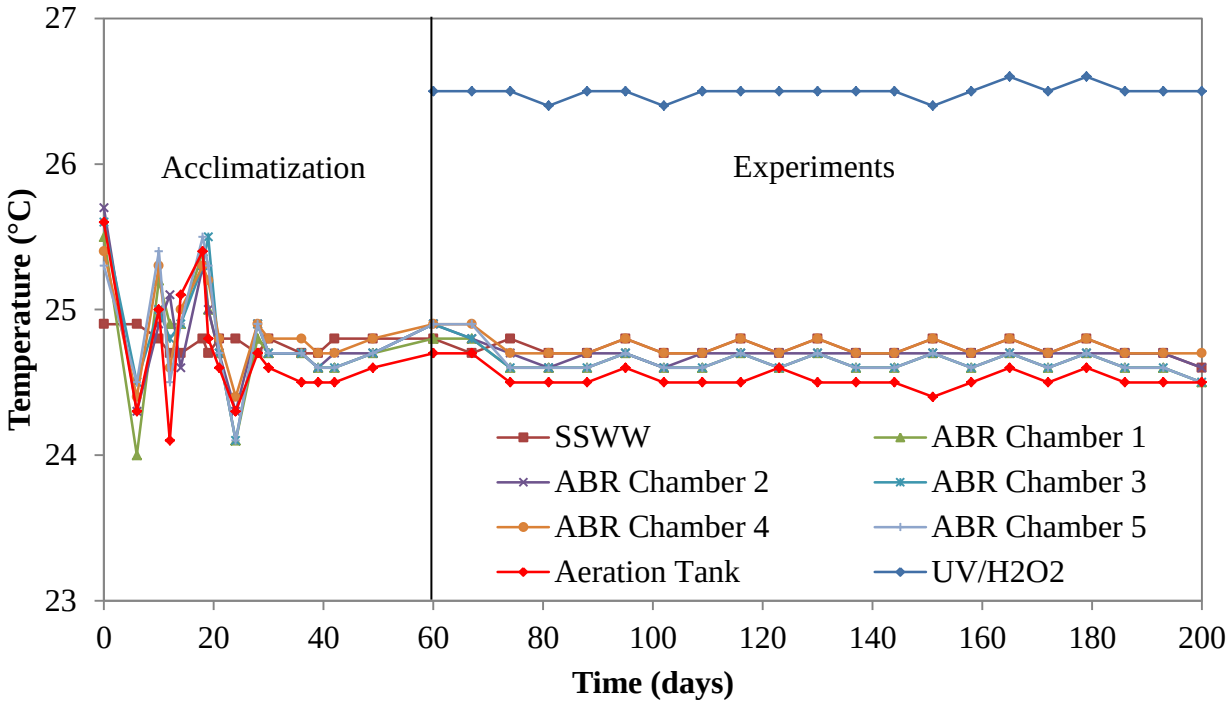


Figure 4.3. SSWW temperature evolution with time in the ABR, the aerobic AS and UV/H_2O_2 reactors.

In contrast, temperature values during experiments within the 5 chambers of the ABR were in the ranges of 24.50–24.70, 24.60–24.70, 24.50–24.70, 24.70–24.80, and 24.50–24.70°C. Likewise, temperature values in the aeration tank were in the range of 24.40–24.60°C. Moreover, from the effluent of the UV/H_2O_2 process, temperature values were in the range from 26.40 to 26.6°C. A summary of the maximum and minimum SSWW temperature values is depicted in Table 4.2.

Table 4.2. Maximum and minimum SSWW temperature values.

	Acclimatization Temperature (°C)		Experiments Temperature (°C)	
Reactor	**Minimum**	**Maximum**	**Minimum**	**Maximum**
ABR Chamber 1	24.00	25.50	24.50	24.70
ABR Chamber 2	24.30	25.70	24.60	24.70
ABR Chamber 3	24.10	25.60	24.50	24.70
ABR Chamber 4	24.40	25.40	24.70	24.80
ABR Chamber 5	24.10	25.50	24.50	24.70
Aeration Tank	24.10	25.60	24.40	24.60
UV/H_2O_2	-	-	26.40	26.60

It was deduced that temperature and pH during experiments were relatively constants compared to those from the acclimatization period due to the final adaptation of the microorganisms to the SSWW characteristics. Both temperature and pH values during experiments remained without significant changes throughout the entire experimental period.

4.2.4. TSS and VSS concentrations of the anaerobic sludge and MLSS and MLVSS concentrations of the aerobic sludge

Figures 4.4 and 4.5 show the TSS and VSS concentrations in the ABR compartments, and it reveals a trend where the microorganisms rapidly adapted to the conditions inside the ABR by gradually increasing the wastewater concentration. These figures show a rapid growth until they reach stabilization. Variations after the 16^{th} day may be attributed to the increase of the wastewater concentration from 20 to 40%. On the other hand, the variation after the 24^{th} day may be attributed to the increase of the wastewater concentration from 40 to 60%. Moreover, from the 30^{th} to the 37^{th} day, microorganisms were in a lapse phase under a wastewater concentration of 80%. Then, after the wastewater concentration was increased from 80 to 100% on the 40^{th} day, a slight increase of the microorganisms' growth was observed. Therefore, it could be concluded that the acclimatization process was successful and the experiments could start. There was no washout observed in the

effluent of the reactors; thus, no sludge was removed. After 60 days of acclimatization, the TSS and VSS concentrations of the inoculum were reached in the ranges of 12,750-21,600 mg/L and 10,600-16,150 mg/L, respectively.

Figures 4.6 and 4.7 show the MLSS and MLVSS concentrations in the aerobic AS reactor, where it is shown a trend where the microorganisms rapidly adapted to the conditions inside the aeration tank, while gradually increasing the wastewater concentration (20, 40, 60, 80, and 100%) for a period of 30 days. These figures also show a rapid growth until they reach stabilization; therefore, it could be concluded that the acclimatization process was successful and the experiments could start. After 30 days of acclimatization, the concentrations of MLSS and MLVSS were reached approximately to 3,718 and 2,399 mg/L, respectively. These results are similar to those observed in previous studies (Cao, 2009; Cao and Mehrvar, 2011).

4.2.5. TSS and VSS concentrations of the SSWW

The TSS and VSS values of the SSWW in the effluents of the ABR and the aerobic AS for the flow rates in the range from 2.93 to 11.70 mL/min are shown in Tables 4.3 and 4.4; where in both anaerobic and aerobic effluents, at higher flow rates, TSS values increased. It was also determined that flow rates greater than 7.80 mL/min exceeded the disposal level according to the Canadian standards for rivers, streams and estuaries (Environment Canada, 2000) and the Ontario standards (ECO, 2010) as depicted in Tables 2.4, 2.5 and 2.6. Therefore, for the combined processes, flow rates of 7.50 mL/min or less were used. On the other hand, it is shown that effluent TSS concentrations of the ABR are higher than those observed using aerobic AS, and this may be attributed to poor sludge settleability in the ABR.

Table 4.3. TSS profiles of the SSWW in the ABR and the aerobic AS.

Q (mL/min)	TSS of SSWW in the ABR (mg/L)	TSS of SSWW in the aerobic AS (mg/L)
2.93	4.69	2.98
3.34	5.09	3.88
3.75	5.23	4.13
4.50	8.01	5.85
4.68	9.35	7.19
7.50	18.68	16.73
7.80	26.11	25.23
11.70	156.39	124.97

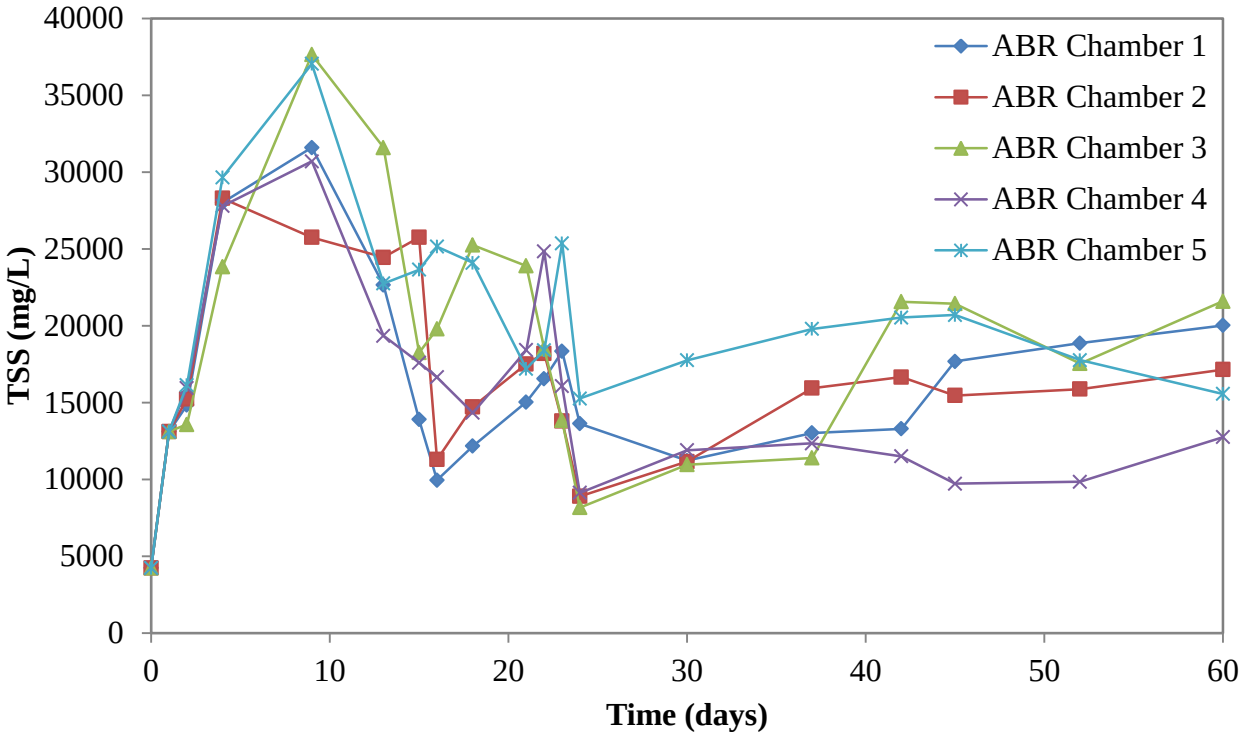


Figure 4.4. TSS profile and evolution with time of the anaerobic sludge within the ABR process.

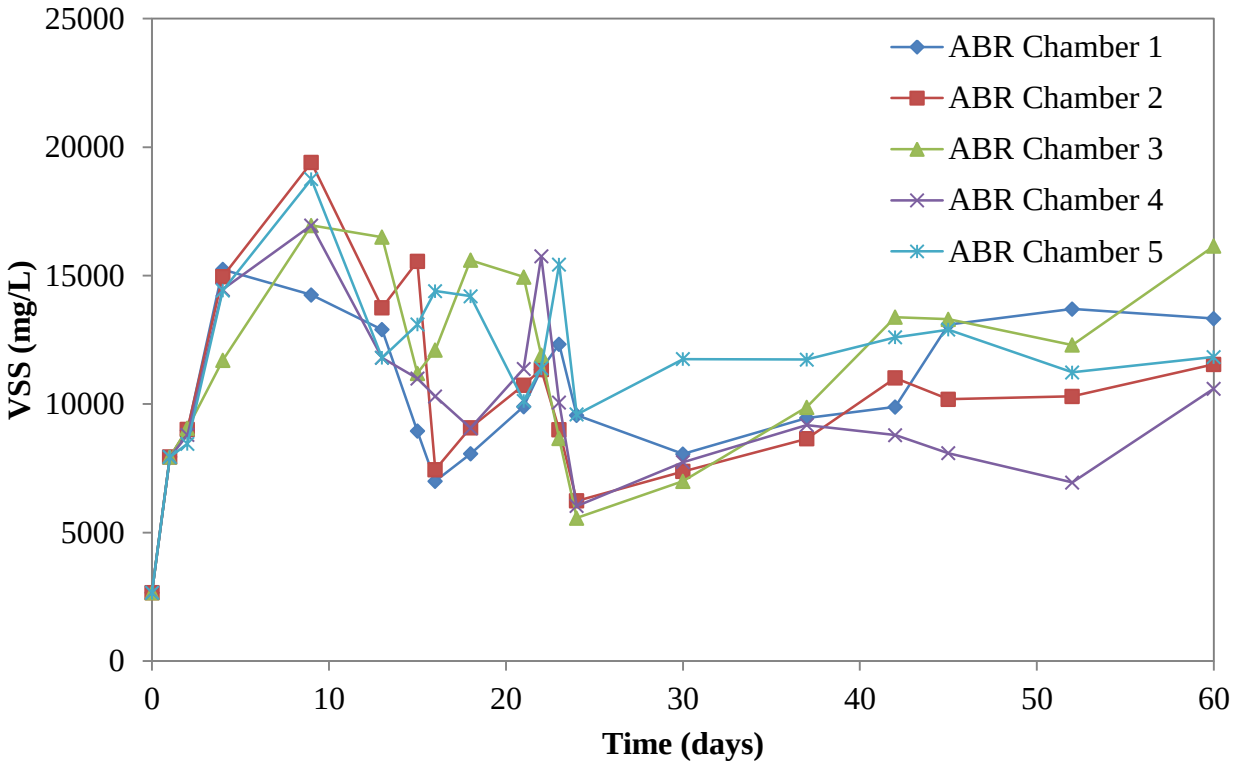


Figure 4.5. VSS profile and evolution with time of the anaerobic sludge within the ABR process.

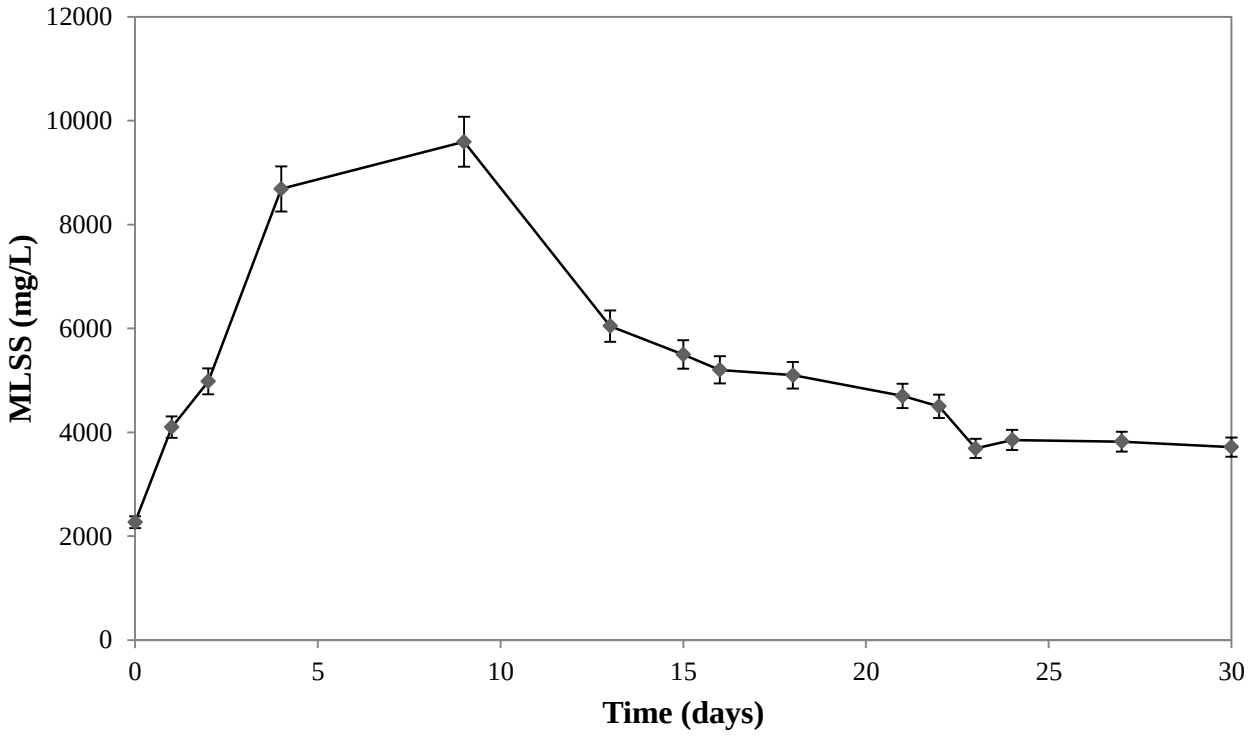


Figure 4.6. MLSS profile and evolution with time of the anaerobic sludge within the aerobic AS process. Error bars represent standard deviations.

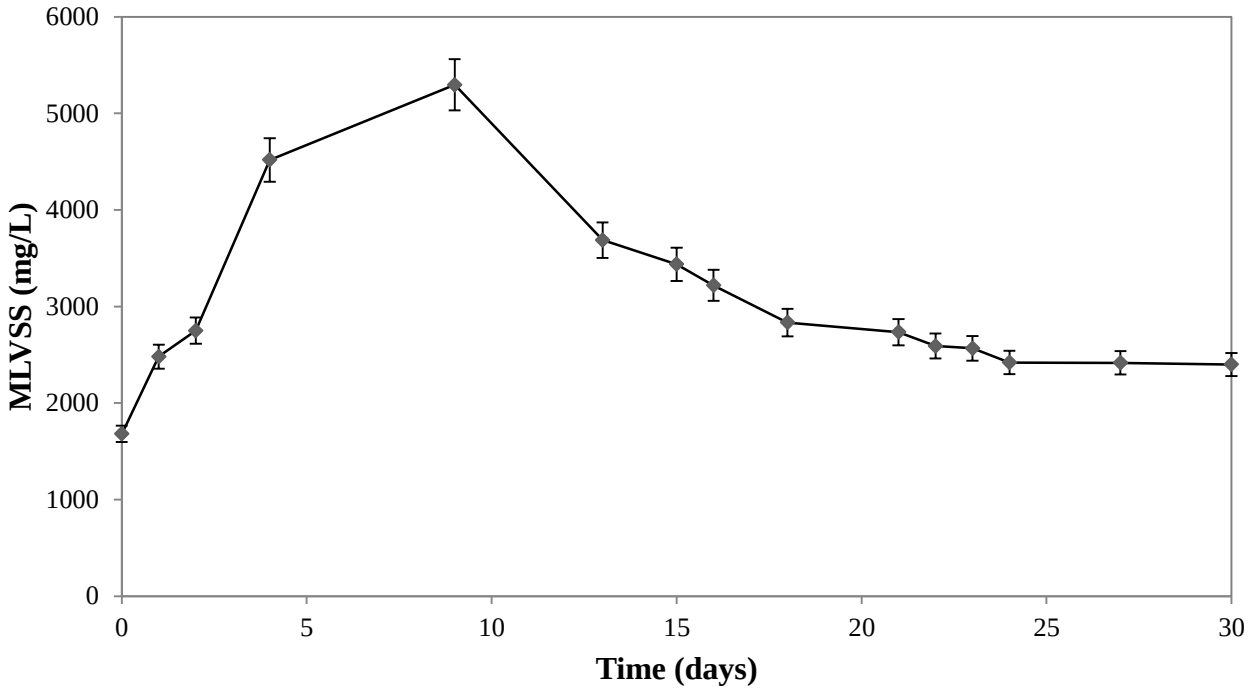


Figure 4.7. MLVSS profile and evolution with time of the anaerobic sludge within the aerobic AS process. Error bars represent standard deviations.

Table 4.4. VSS profiles of the SSWW in the ABR and the aerobic AS.

Q (mL/min)	VSS of SSWW in the ABR (mg/L)	VSS of SSWW in the aerobic AS (mg/L)
2.93	3.75	2.38
3.34	4.07	3.10
3.75	4.18	3.30
4.50	6.41	4.68
4.68	7.48	5.75
7.50	14.94	13.38
7.80	20.89	20.18
11.70	125.11	99.98

4.3. TOC and TN removal in SSWW using individual anaerobic and aerobic processes

Biological treatment using an ABR and aerobic AS at a laboratory scale were studied to treat SSWW with TOC loadings of 0.03–1.01 g/(L day), TN loadings of 0.01–0.19 g/(L day), and flow rates of 2.93 to 11.70 mL/min. The results shown in Figure 4.8 revealed that both processes achieve a good efficiency to treat the SSWW for TOC removal in a range of 84.06 to 95.03%. Likewise, Figure 4.9 shows the results of TN removal, in the range of 31.32 to 73.46% for both processes. The lower performance was obtained with the ABR for an influent concentration of 183.35 mgTOC/L and 63.38 mgTN/L at the HRT of 7 days and a flow rate of 3.34mL/min with up to 84.06% TOC removal and 31.32% TN removal. Likewise, the best performance was obtained with the aerobic AS for an influent concentration of 1,008.85 mgTOC/L and 254.23 mgTN/L with up to 95.03% TOC removal and 73.46% TN removal. These results are comparable to those found in previous studies (Cao, 2009; Cao and Mehrvar, 2011). Furthermore, it is also deduced that at higher influent TOC and TN concentrations, the TOC and TN removal rates are higher (5% and 15%, respectively), whereas the performance of the first three chambers of the ABR is decreased by approximately 30%, which may be attributed to the bioavailability of the organic matter and the acetogenesis.

Moreover, Figures 4.10 and 4.11 show the effects of HRT on TOC and TN removal using biological treatment for an influent concentration of 639.44.85 mgTOC/L and 144.40 mgTN/L; where at a HRT of 5 days, the TOC removal rate was reached to 83.64 and 89.66% on the ABR and the aerobic AS processes, respectively. Likewise, at a HRT of 8 days, the TOC removal rate was reached to 88.88 and 94.26% in the ABR and the aerobic AS processes, respectively. Similarly, at a HRT of 5 days, the TN removal was reached to 36.49 and 43.19% in the ABR and the aerobic AS processes, respectively. In contrast, at a HRT of 8 days, the TN removal rate reached 51.52 and 75.15% in the

ABR and the aerobic AS processes, respectively. Thus, it is perceived that the TOC and TN removal were significantly higher by prolonging the HRT.

In spite of the results from previous studies (Cao, 2009; Cao and Mehrvar, 2011), a good removal of TN, in the range from 31.32 to 73.46%, was achieved by varying the flow rate and influent concentration of the SSWW; this may be attributed to the well maintained conditions in the systems, where DO concentrations were in the ranges of 0.2–1.2 mg/L and 0.4–3.2 mg/L for the ABR and the aerobic AS, respectively. Therefore, DO concentrations of above 1.0 mg/L permitted nitrification, whereas DO concentrations of below 0.5 mg/L permitted denitrification.

4.4. TOC and TN removal in SSWW using combined anaerobic-aerobic systems

Although individual processes of both anaerobic and aerobic processes are significantly efficient to treat the SSWW as shown in the previous section, combined anaerobic and aerobic systems performed higher efficiencies as discussed in the following sections.

4.4.1. TOC and TN removal in SSWW using combined anaerobic-aerobic processes

As depicted in Figures 4.12 and 4.13, up to 96.36% TOC and 80.53% TN removal rates were obtained for influent concentrations of 1,008.85 mgTOC/L and 419.77 mgTN/L, HRT of 6.24 days, and a flow rate of 3.75mL/min, while 93.15% TOC and 33.21% TN removal rates were obtained for influent concentrations of 1,008.85 mgTOC/L and 419.77 mgTN/L, HRT of 3.12 days, and a flow rate of 7.50mL/min using combined ABR and aerobic AS.

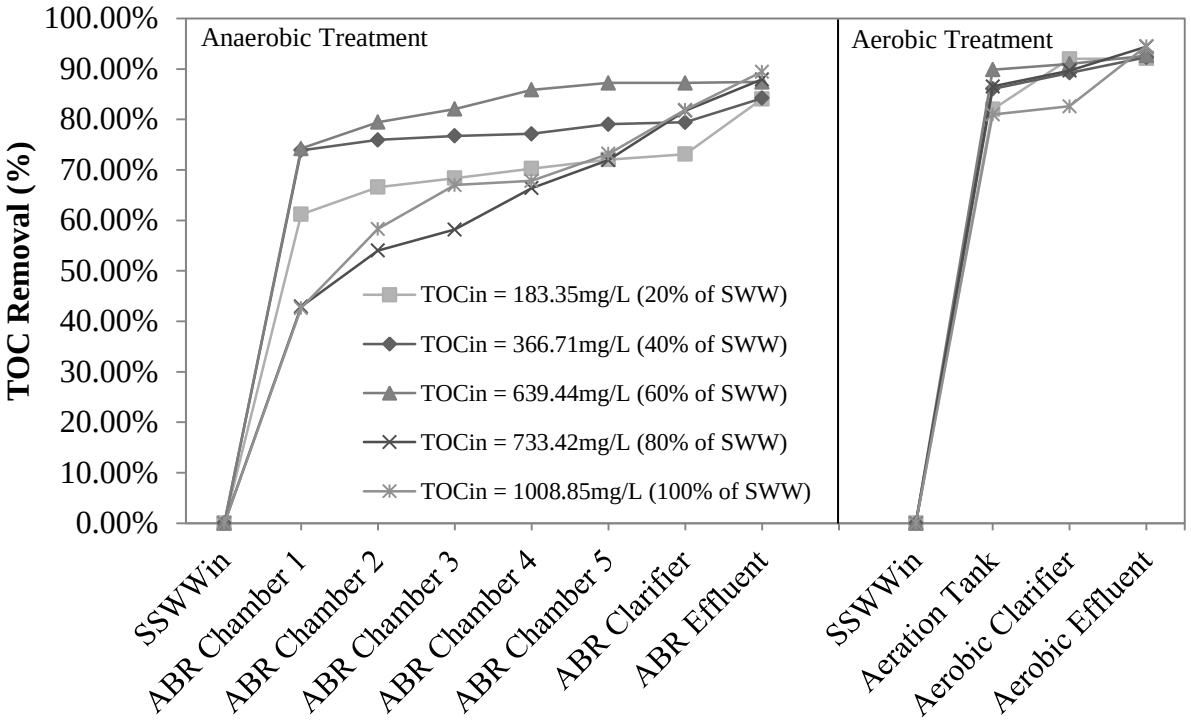


Figure 4.8. TOC removal for different wastewater concentrations using biological treatment at the HRT of 7 days and a flow rate of 3.34 mL/min in continuous mode without recycling.

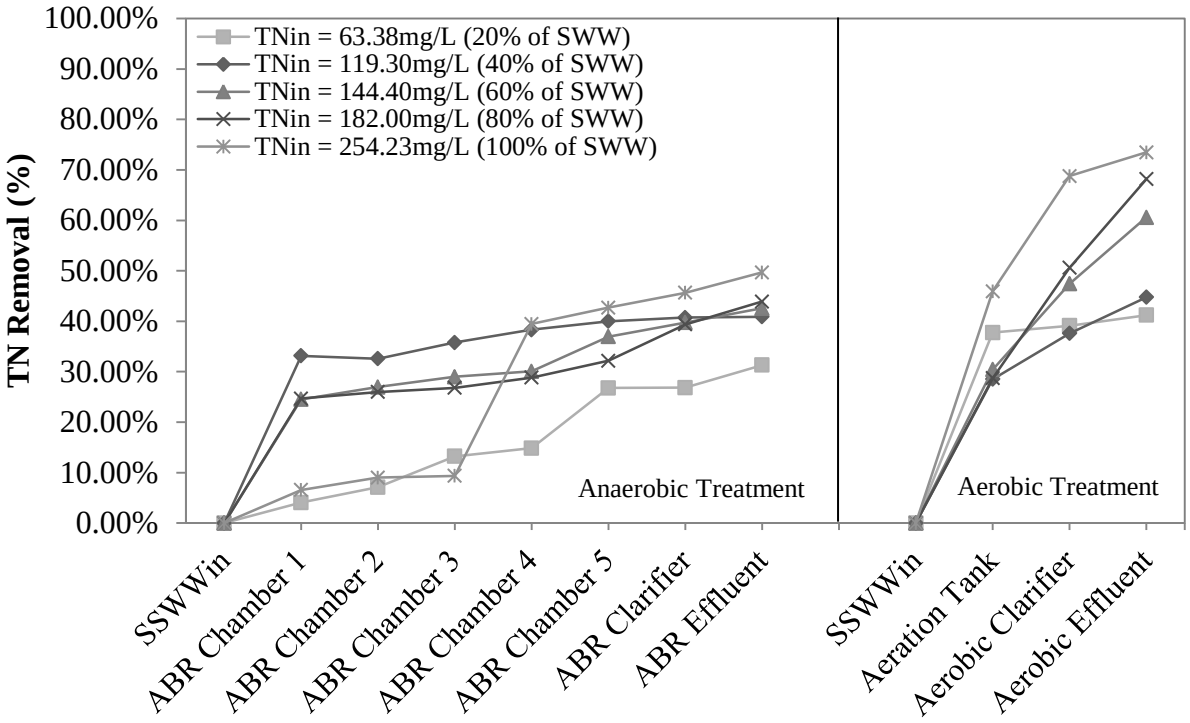


Figure 4.9. TN removal for different wastewater concentrations using biological treatment at the HRT of 7 days and a flow rate of 3.34 mL/min in continuous mode without recycling.

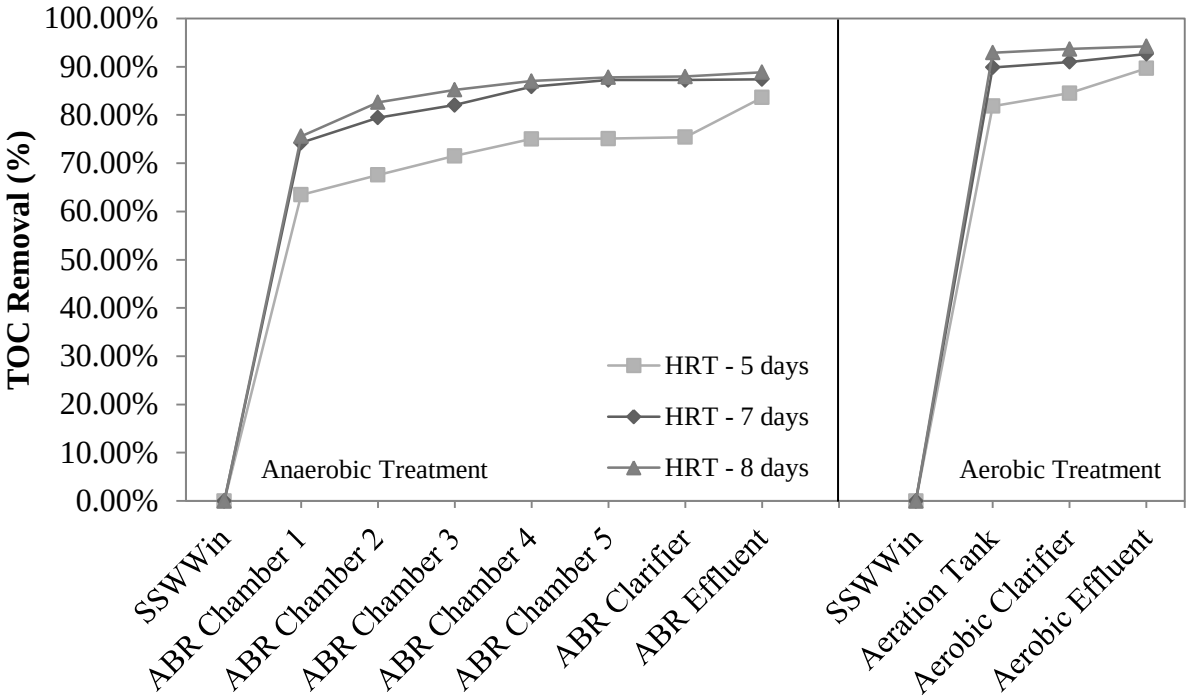


Figure 4.10. Effects of HRT on TOC removal using biological treatment with TOC concentration in the inlet of 639.44 mg/L (60% of SWW) in continuous mode without recycling.

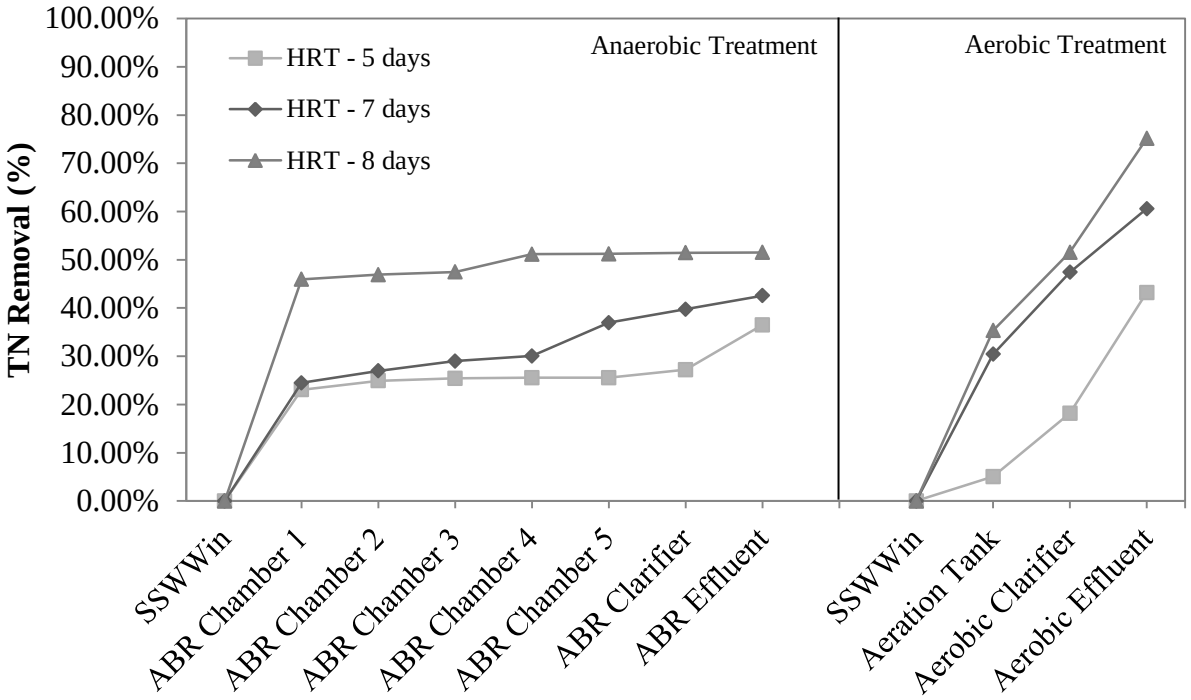


Figure 4.11. Effects of HRT on TN removal using biological treatment with TN concentration in the inlet of 144.40 mg/L (60% of SWW) in continuous mode without recycling.

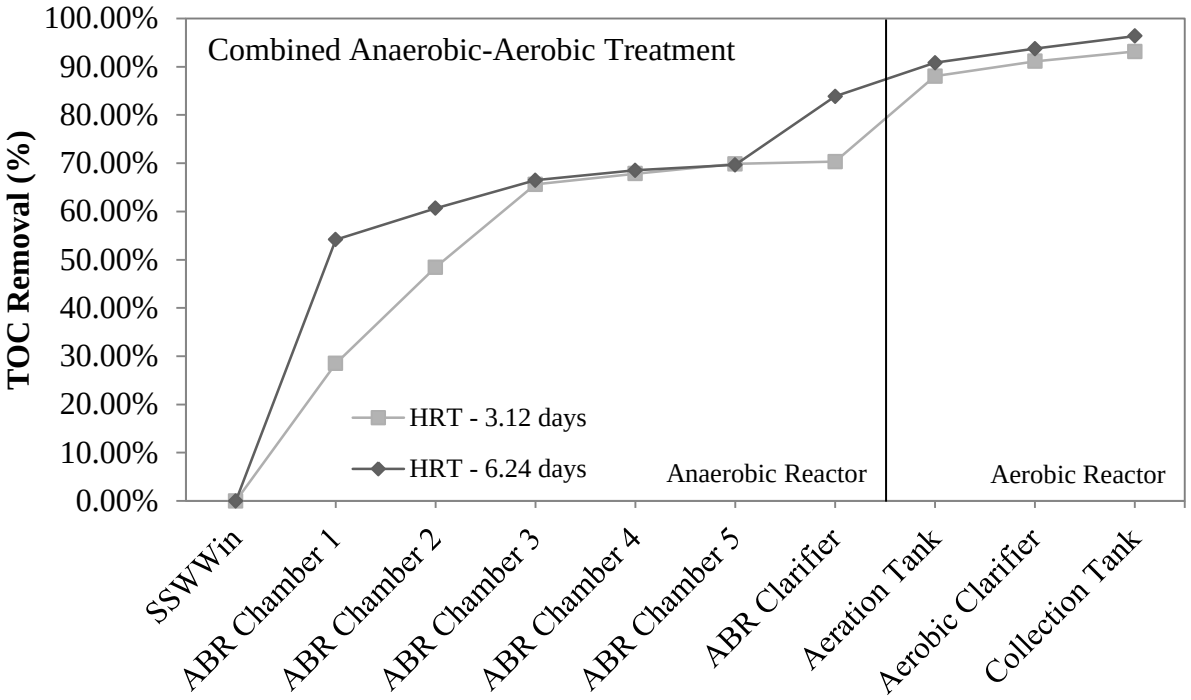


Figure 4.12. Effects of HRT on TOC removal by combined anaerobic-aerobic processes with TOC concentration in the inlet of 1,008.85 mg/L (100% of SWW) in continuous mode without recycling.

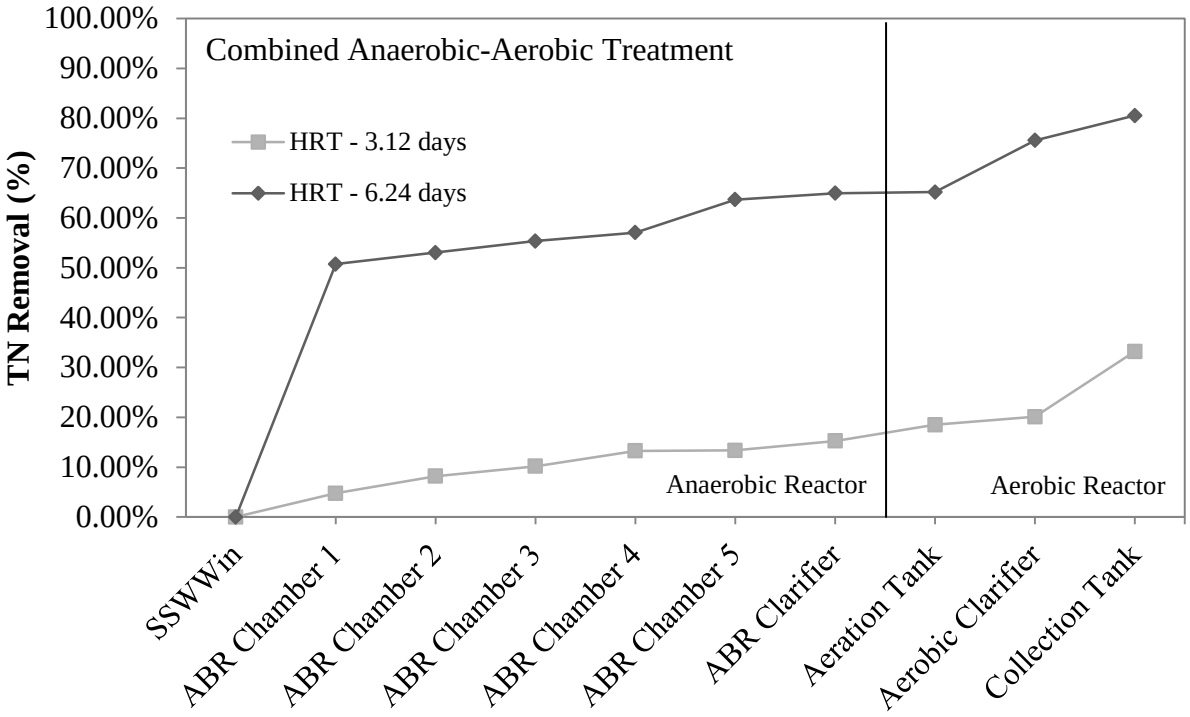


Figure 4.13. Effects of HRT on TN removal by combined anaerobic-aerobic processes with TN concentration in the inlet of 419.77 mg/L (100% of SWW) in continuous mode without recycling.

4.4.2. TOC and TN removal in SSWW using combined aerobic-anaerobic processes

By making the aerobic stage the first step of the combined processes, higher TOC and TN removal rates were also reached compared to those of individual processes, as shown in Figures 4.14 and 4.15, respectively. In the case of aerobic-anaerobic processes, up to 96.10% TOC and 76.44% TN removal rates were obtained for influent concentrations of 1,008.85 mgTOC/L and 425.54 mgTN/L, at a HRT of 6.24 days, and a flow-rate of 3.75mL/min, while 86.04% TOC and 29.41% TN removal rates were obtained for influent concentrations of 1,008.85 mgTOC/L and 425.54 mgTN/L, HRT of 3.12 days, and a flow-rate of 7.50mL/min.

Both combined biological processes achieved good results in treating SSWW, with TOC and TN removal rates of above 95 and 75%, respectively. Up to 96.36% TOC and 80.53% TN removal rates were reached by combined anaerobic-aerobic processes, while, up to 96.10% TOC and 76.44% TN removal rates were attained by combined aerobic-anaerobic processes. Thus, it was determined that combined anaerobic-aerobic processes have a considerable advantage in combined aerobic-anaerobic processes of approximately 0.26% TOC and 4.09% TN removal rates. Therefore, it was recommended to use combined anaerobic-aerobic processes for following experiments. Accordingly, an adequate combination of anaerobic and aerobic processes is essential for the biological removal of nutrients (N and P), as depicted in the obtained TN removal by combining anaerobic-aerobic systems (Del Pozo and Diez, 2003; Ahn et al., 2007; Liu et al., 2008; Chan et al., 2009).

4.4.3. TOC and TN removal in SSWW using combined anaerobic-aerobic processes with recycling

An experiment was conducted with the recycling mode, in which the SSWW treated in the aerobic AS reactor was recycled into the ABR, in order to evaluate the performance of the combined anaerobic-aerobic processes and to analyze the impact on TN removal. For this experiment, an influent concentration of 639.44 mgTOC/L and 144.40 mgTN/L and a flow-rate of 7.50mL/min were used.

Results shows that recycling the flow from the aerobic AS into the ABR did not significantly decrease either TOC or TN concentrations. As depicted in Figures 4.16 and 4.17, a minimum variation of 0.02 and 0.05% was observed for TOC and TN removal rates, whereas the HRT of the recycling mode system doubles that of the combined anaerobic-aerobic processes; thus, making the combined system with recycling less efficient than without recirculating the flow.

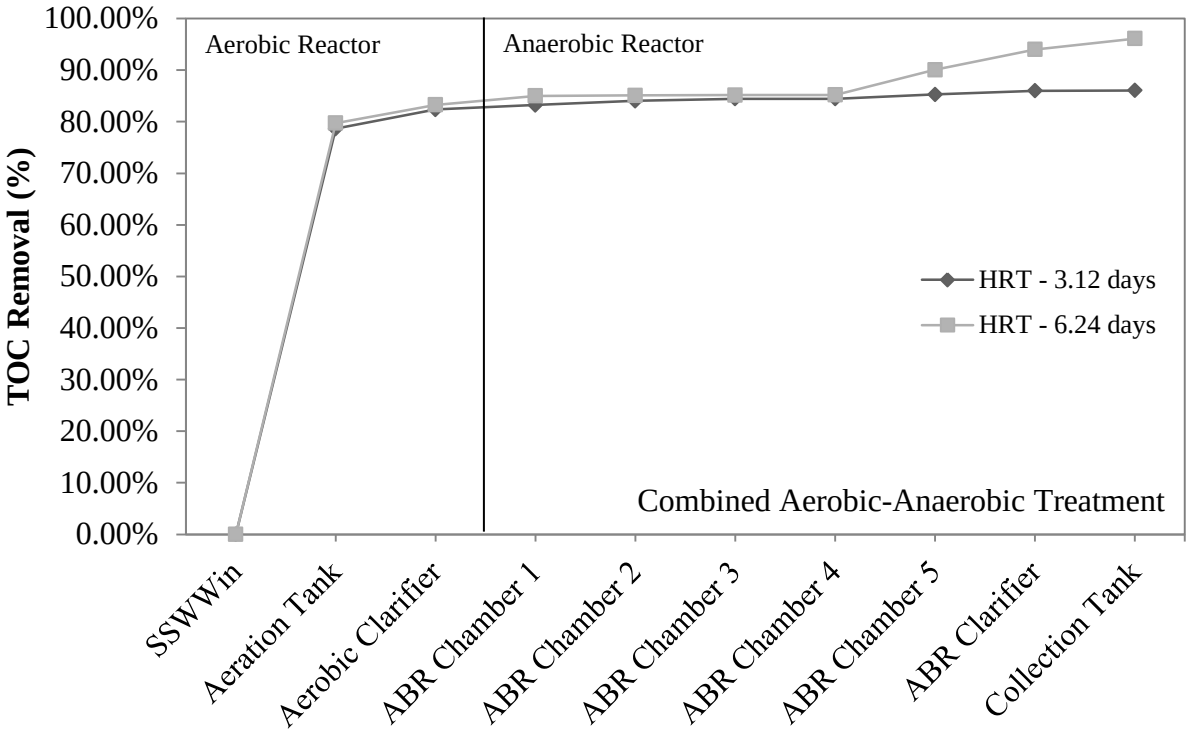


Figure 4.14. Effects of HRT on TOC removal by combined aerobic-anaerobic processes with TOC concentration in the inlet of 1,008.85 mg/L (100% of SWW) in continuous mode without recycling.

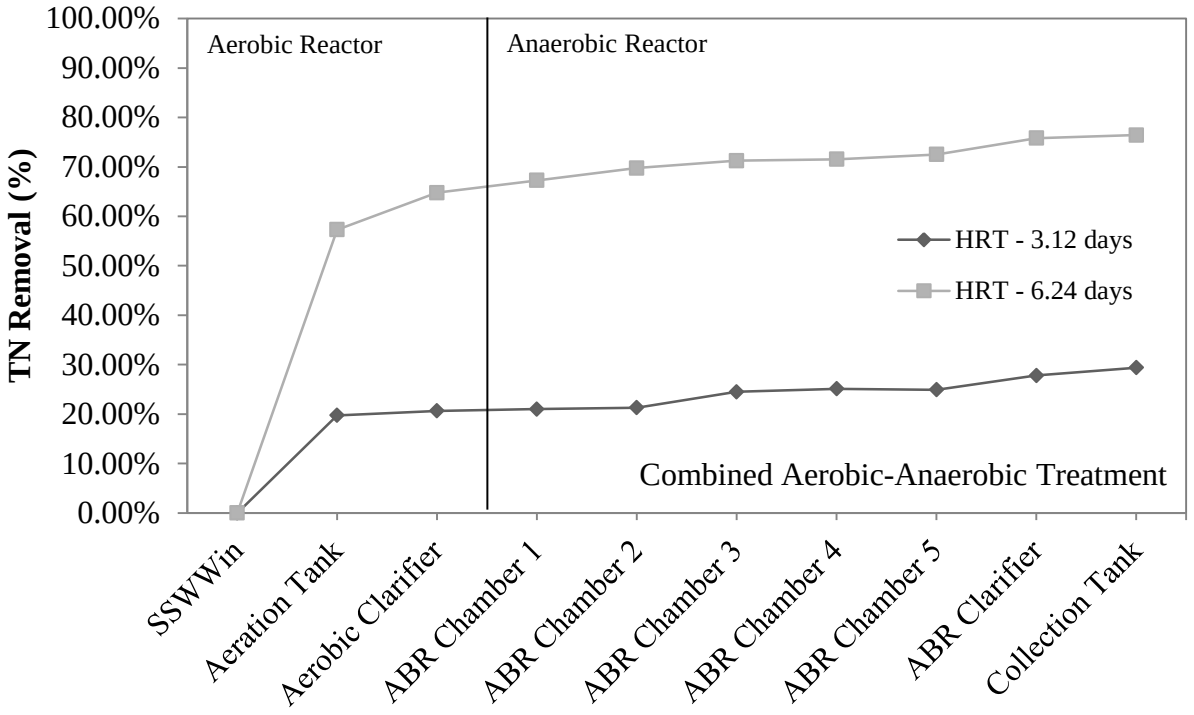


Figure 4.15. Effects of HRT on TN removal by combined aerobic-anaerobic processes with TN concentration in the inlet of 425.54 mg/L (100% of SWW) in continuous mode without recycling.

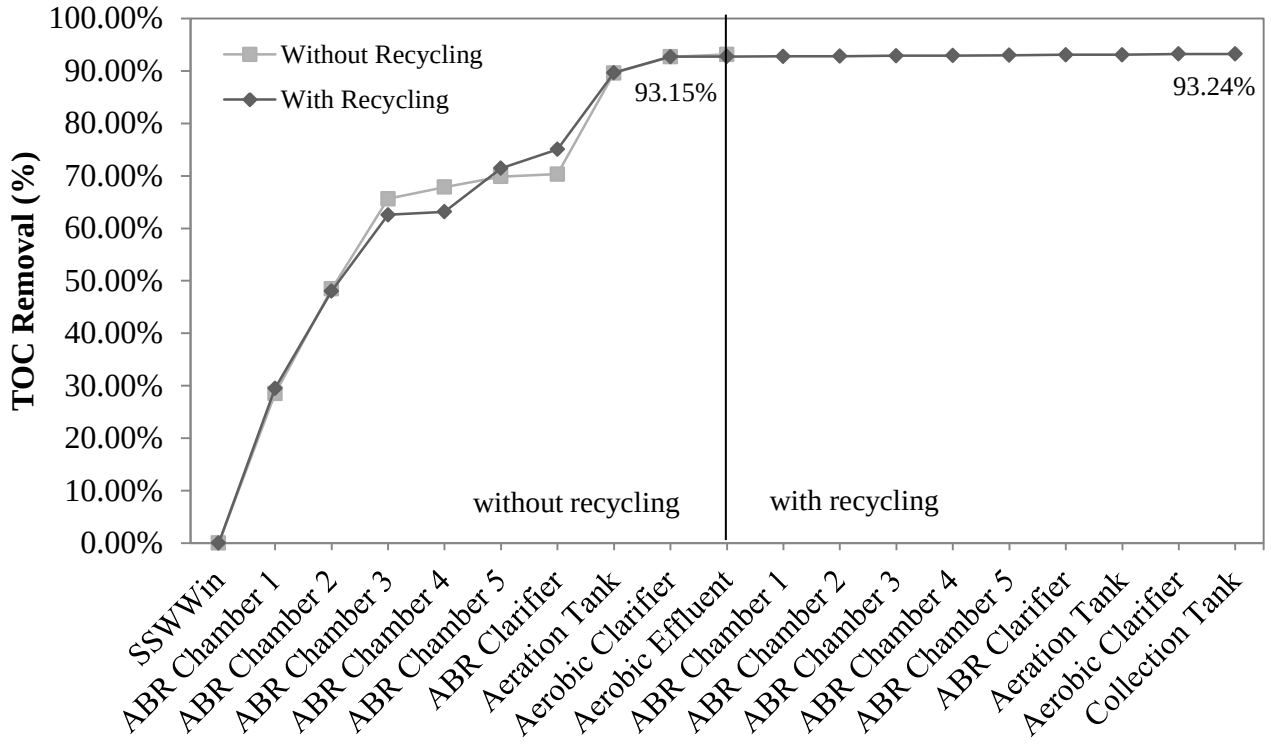


Figure 4.16. Comparison of TOC removal by means of combined anaerobic-aerobic processes with and without recycling, by using TOC concentration in the inlet of 639.44 mg/L and flow rate of 7.50 mL/min in continuous mode.

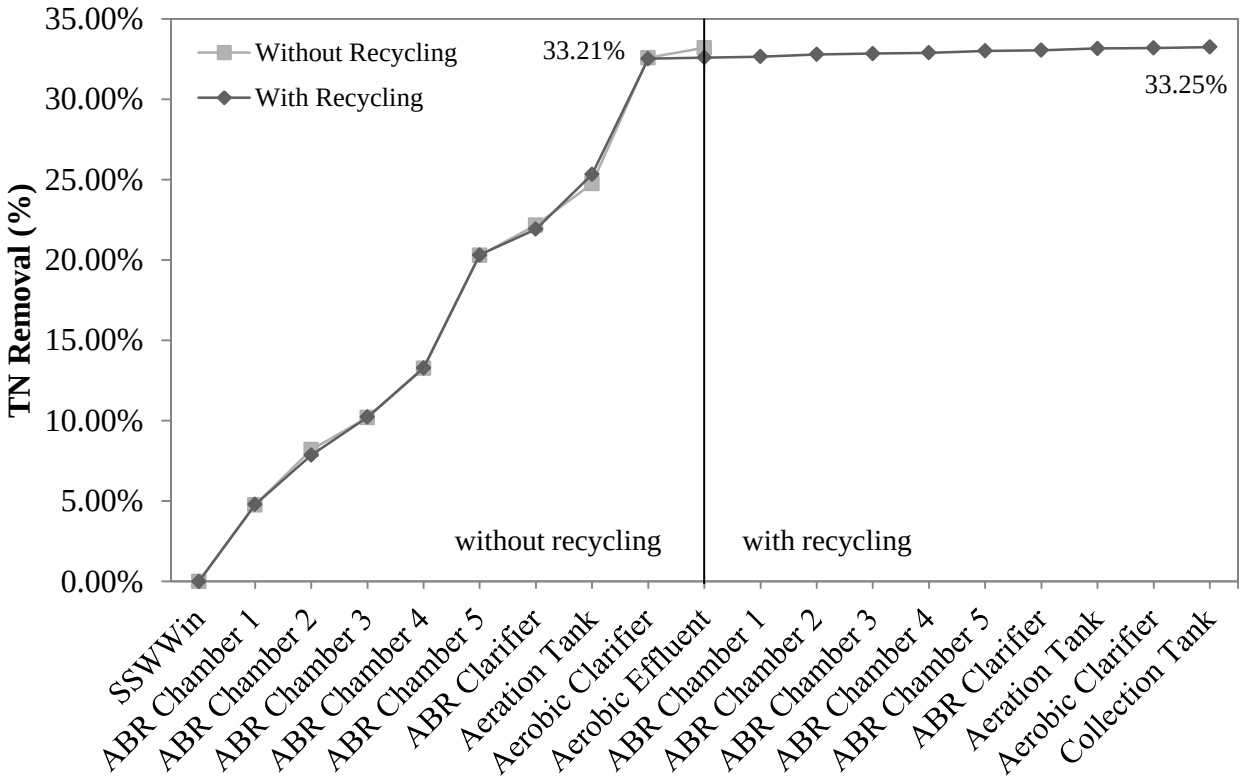


Figure 4.17. Comparison of TN removal by means of combined anaerobic-aerobic processes with and without recycling, by using TN concentration in the inlet of 144.40 mg/L and flow rate of 7.50 mL/min in continuous mode.

4.5. TOC and TN removal in SSWW using UV/H_2O_2 process alone

The UV/H_2O_2 process alone was studied to treat SSWW with TOC and TN loadings of 64.88–349.84, and 18.10–111.43 mg/L, respectively. Temperature and pH remained constant in the range of 26.40–26.60°C and 6.18–6.20, respectively, except in the dark experiments, where temperature was in the ranges of 21.10–21.50°C. There was no analysis of different intermediates that may be formed during the UV/H_2O_2 treatment.

Figures 4.18, 4.19, and 4.20 show the TOC removal of the raw SSWW being treated by the UV/H_2O_2 process alone using different H_2O_2 concentrations (0, 100, 300, 600, 900, 1200, 1500, and 2000 mg/L) at the initial TOC concentrations of 64.88, 163.69, and 348.84 mg/L in continuous mode without recycling. It was determined that by using UV light solely there was no significant TOC removal, the maximum value was 6.96% at HRT of 180 min and TOC_{in} of 64.88 mg/L. On the other hand, it was shown that an optimum H_2O_2 dosage should be determined since an overdose of H_2O_2 will negatively affect the organic removal by $^{\bullet}OH$ recombination, as shown in Reaction (2.26).

Figure 4.21 shows the maximum TOC removal for different SSWW concentrations using UV/H_2O_2 treatment at a HRT of 3 h in continuous mode without recycling. This figure illustrates a trend, where it may be stated that by increasing the SSWW concentration, the TOC removal capacity decreases due to the presence of more organic matter ready to compete for $^{\bullet}OH$ and the production of intermediates, which tends to lower the efficiency of the UV/H_2O_2 process. The results revealed a reasonable efficiency; up to 75.22% TOC removal was obtained for an influent concentration of 64.88 mgTOC/L at the HRT of 180 min with H_2O_2 concentration of 900 mg/L. These results are in accordance with the previous studies of Cao (2009), Cao and Mehrvar (2011), Barrera (2011), and Barrera et al. (2011).

In contrast, Figures 4.22, 4.23, and 4.24 show the possible TN removal of the SSWW being treated by the UV/H_2O_2 using different H_2O_2 concentrations (0, 100, 300, 600, 900, 1200, 1500 and 2000 mg/L) at the initial TN concentrations of 18.10, 40.02 and 93.94 mg/L. It was determined that there was no significant removal of TN using UV/H_2O_2 process for the treatment of SSWW. Figure 4.25 confirms that the UV/H_2O_2 process is not able to remove TN from SSWW, showing a maximum variation of 5.99%. Therefore, this section is focused on TOC removal using the UV/H_2O_2 process.

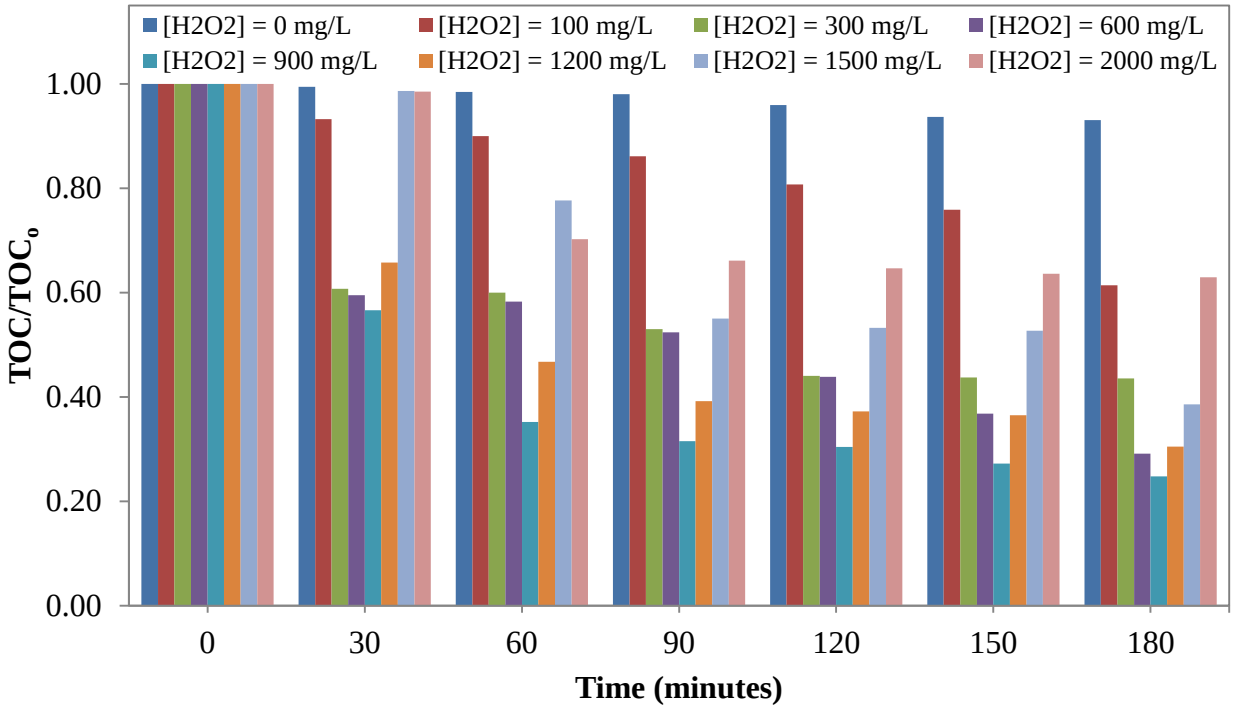


Figure 4.18. TOC removal in untreated SSWW using different H_2O_2 concentrations with TOC concentration in the inlet of 64.88 mg/L (5% of SSWW) in the UV/H_2O_2 process alone.

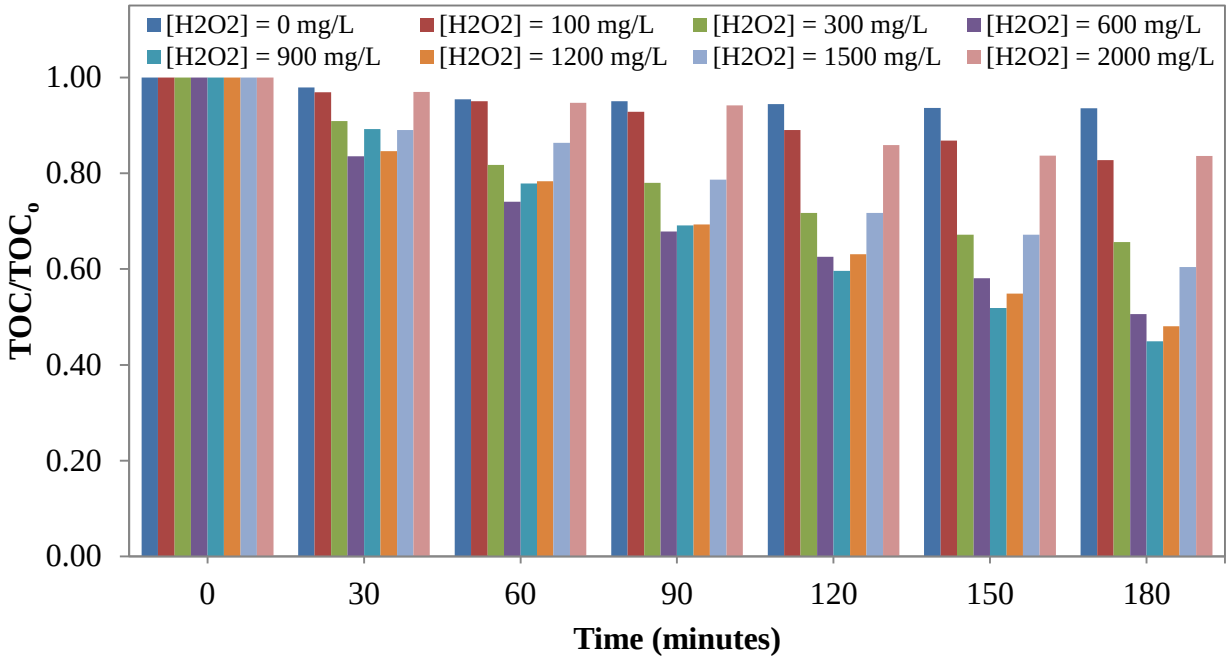


Figure 4.19. TOC removal in untreated SSWW using different H_2O_2 concentrations with TOC concentration in the inlet of 163.69 mg/L (10% of SSWW) in the UV/H_2O_2 process alone.

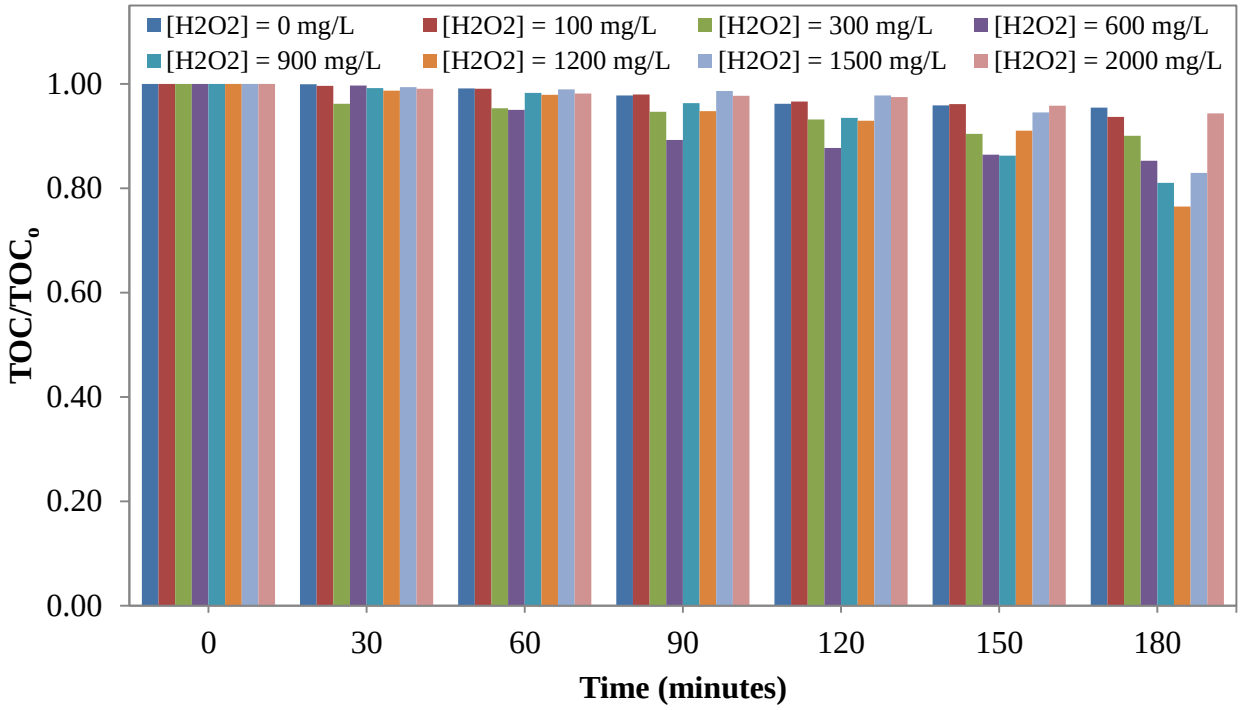


Figure 4.20. TOC removal in untreated SSWW using different H_2O_2 concentrations with TOC concentration in the inlet of 348.84 mg/L (25% of SSWW) in the UV/H_2O_2 process alone in continuous mode without recycling.

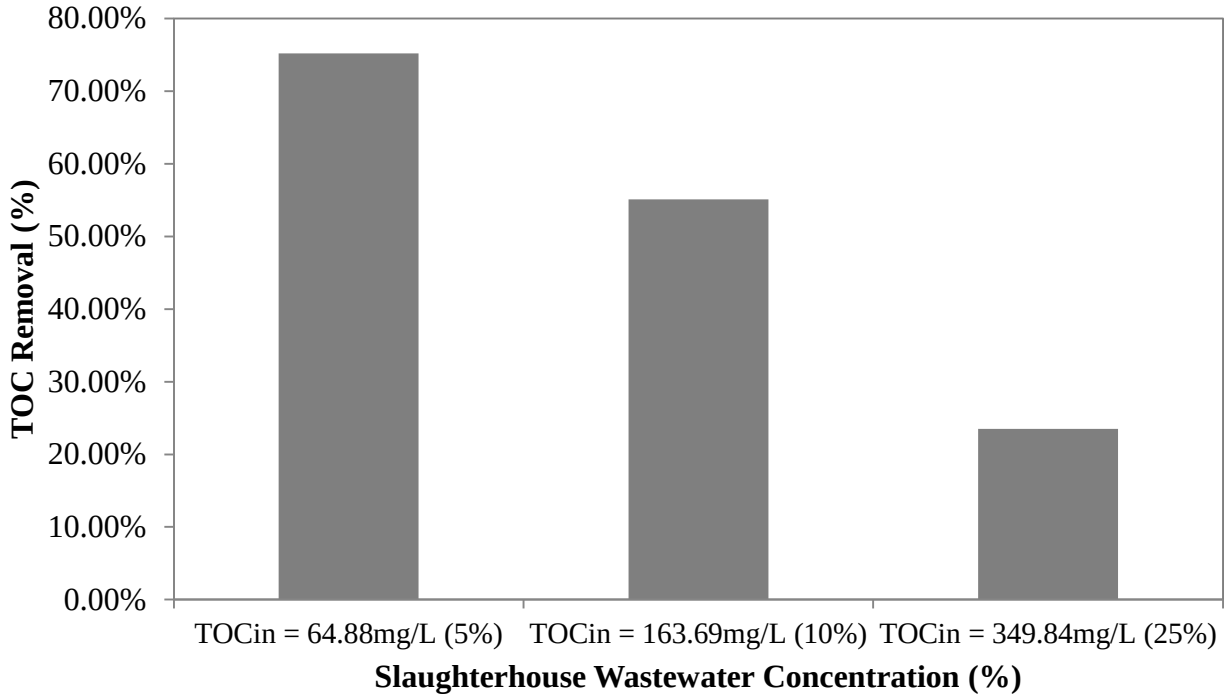


Figure 4.21. Maximum TOC removal for different raw SSWW concentrations using UV/H_2O_2 process alone (HRT = 3 h) in continuous mode without recycling.

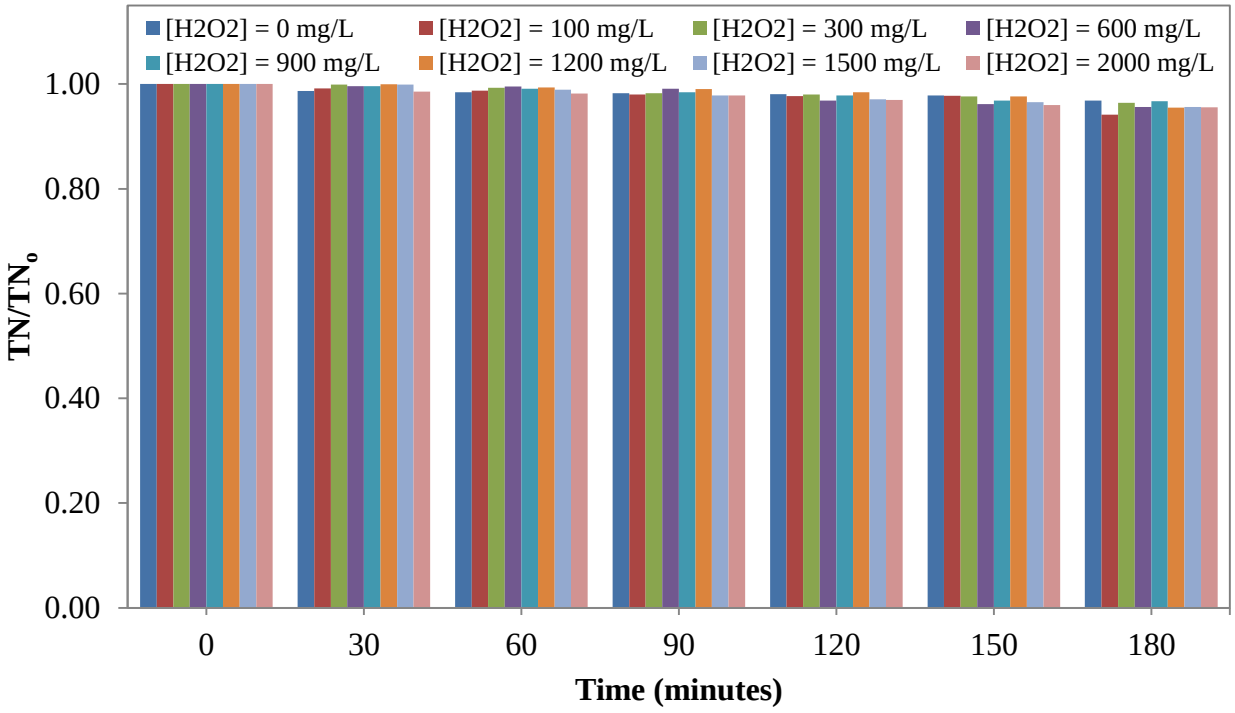


Figure 4.22. TN removal in raw SSWW using different H_2O_2 concentrations with TN concentration in the inlet of 18.10 mg/L (5% of SSWW) in the UV/H_2O_2 process alone in continuous mode without recycling.

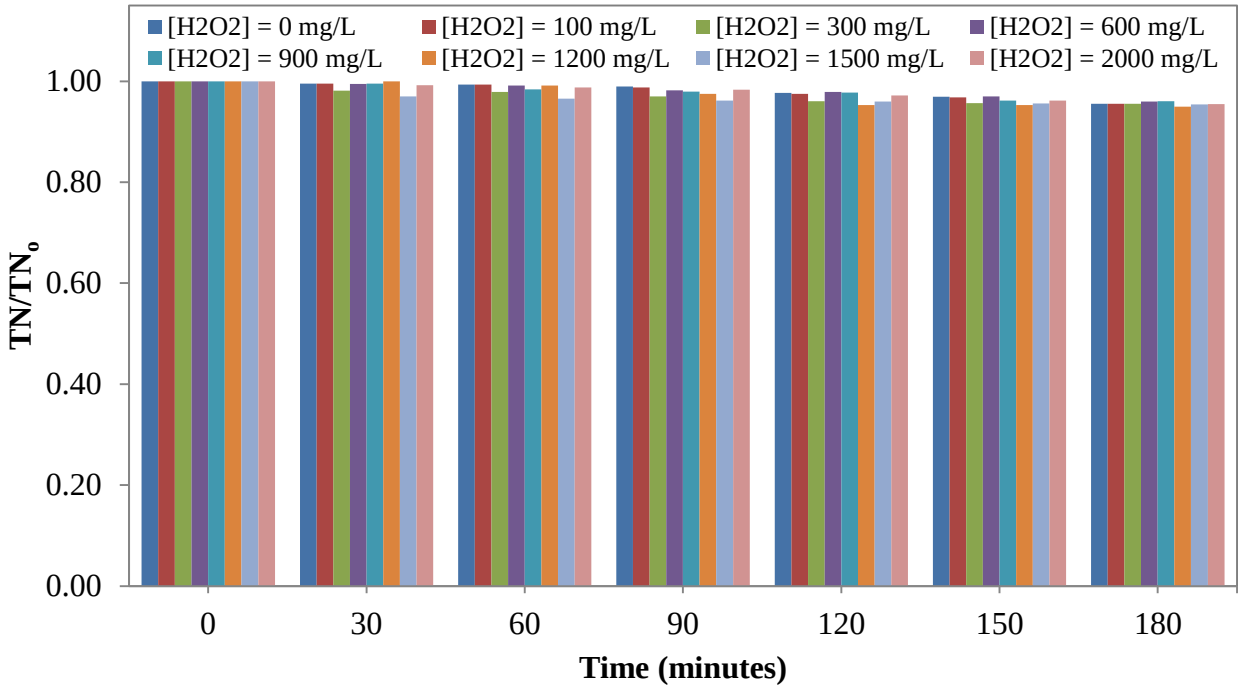


Figure 4.23. TN removal in raw SSWW using different H_2O_2 concentrations with TN concentration in the inlet of 40.02 mg/L (5% of SSWW) in the UV/H_2O_2 process alone in continuous mode without recycling.

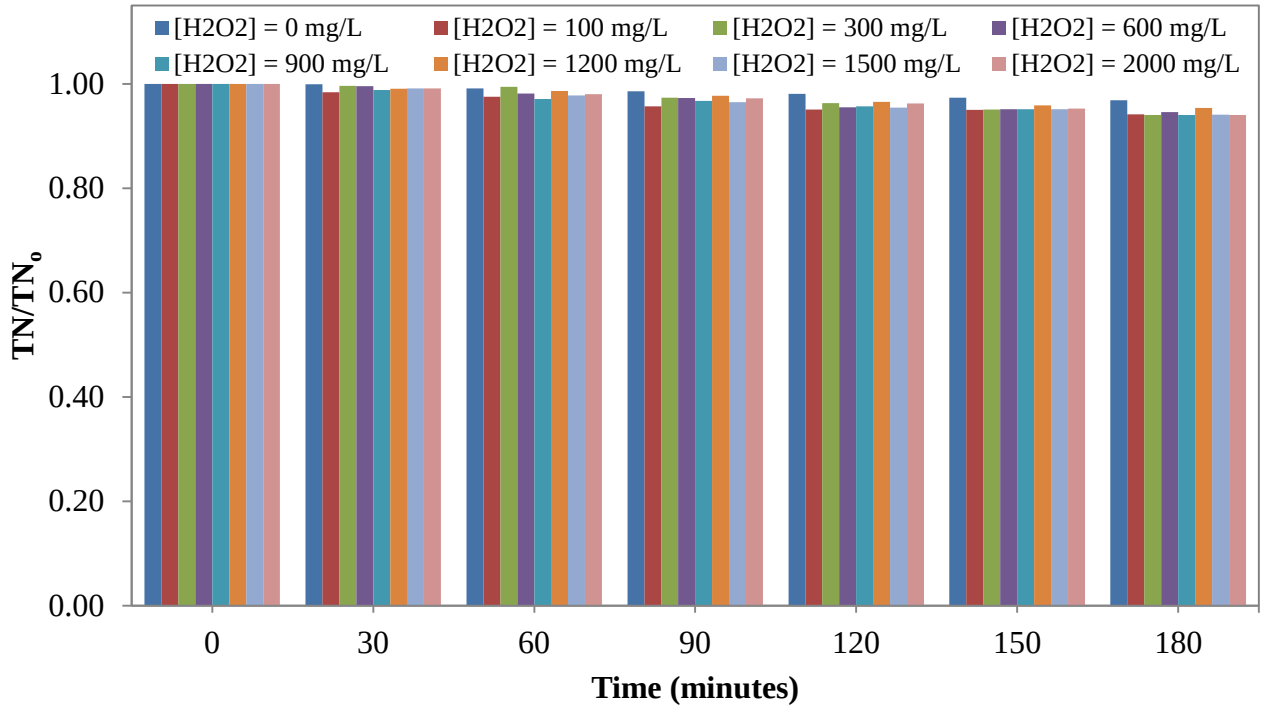


Figure 4.24. TN removal in raw SSWW using different H_2O_2 concentrations with TN concentration in the inlet of 93.94 mg/L (25% of SSWW) in the UV/H_2O_2 process alone in continuous mode without recycling.

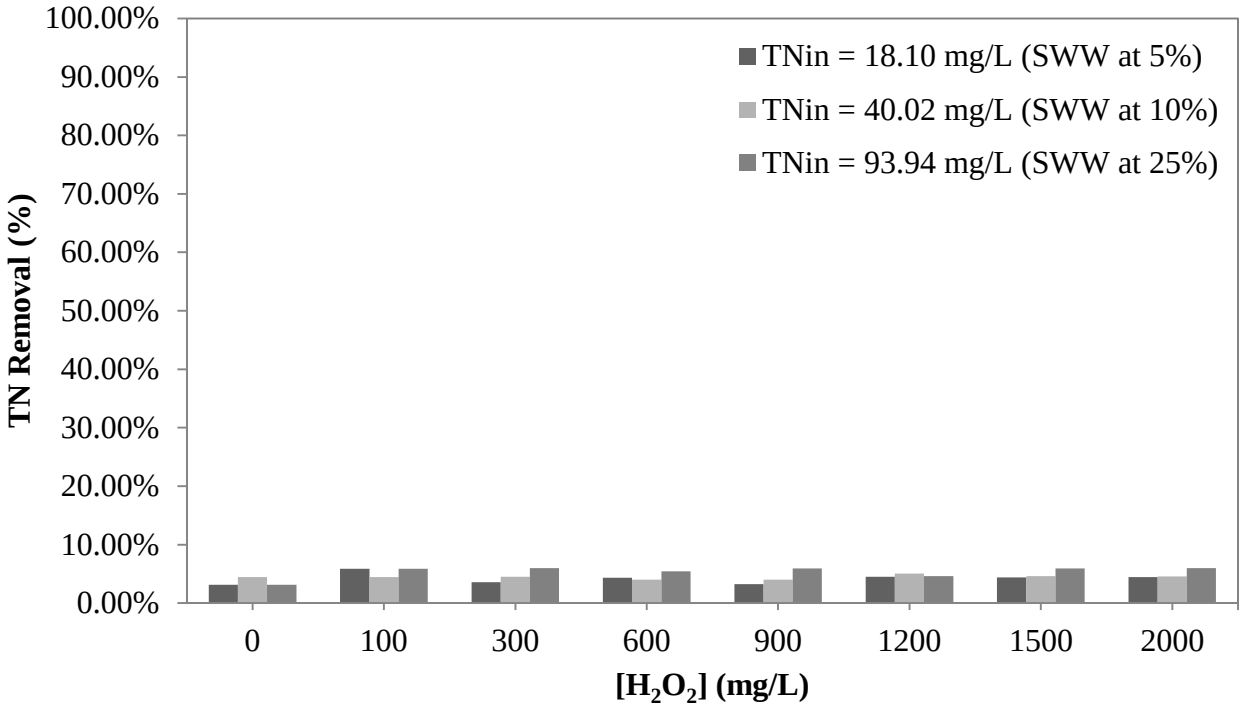


Figure 4.25. TN removal for different raw SSWW concentrations using UV/H_2O_2 process alone in continuous mode without recycling.

4.5.1. Dark experiments

Dark experiments were conducted to analyze the possible loss of organic matter through adsorption on the walls of the photoreactor or by volatilization. The SSWW was pumped into the system with the UV lamps off. Figures 4.26 and 4.27 show TOC and TN removal rates for the dark experiments with no UV radiation present by varying H_2O_2 concentration (0, 900 and 2000 mg/L). It was determined that TOC and TN concentrations remained constant with only a maximum variation of 1.87 and 0.86% for TOC and TN decrease, respectively. It was affirmed that there was no significant organic matter adsorption to the reactor walls or material losses due to volatilization; subsequently any degradation can be attributed to the action of the UV/H_2O_2 process itself. Table 4.5 shows a summary of the results of the dark experiments at a HRT of 180 min.

Table 4.5. TOC and TN values during dark experiments using different UV/H_2O_2 concentrations.

[H_2O_2] (mg/L)	Parameter (mg/L)	Influent	Effluent*	% removal
0	TOC	64.8821	63.8854	1.54%
	TN	18.1044	17.9811	0.68%
900	TOC	64.8848	63.6693	1.87%
	TN	18.1049	17.9501	0.86%
2000	TOC	64.8842	63.7693	1.72%
	TN	18.1042	17.9716	0.73%

* after a HRT of 3 h

4.5.2. Optimal H_2O_2 dosage and molar ratio of [H_2O_2]/[TOC] for the UV/H_2O_2 process

It is well known that H_2O_2 produces hydroxyl radicals in the presence of UV radiation. However, it is important to determine an optimum dosage to be added to the process, since an overdose of the oxidant can lead to negative effects in organics removal due to the recombination of hydroxyl radicals ($^{\bullet}$OH), as shown in Reaction (2.26), whereas a low dosage will reduce the $^{\bullet}$OH production; and thus, lower efficiency of the process for both cases.

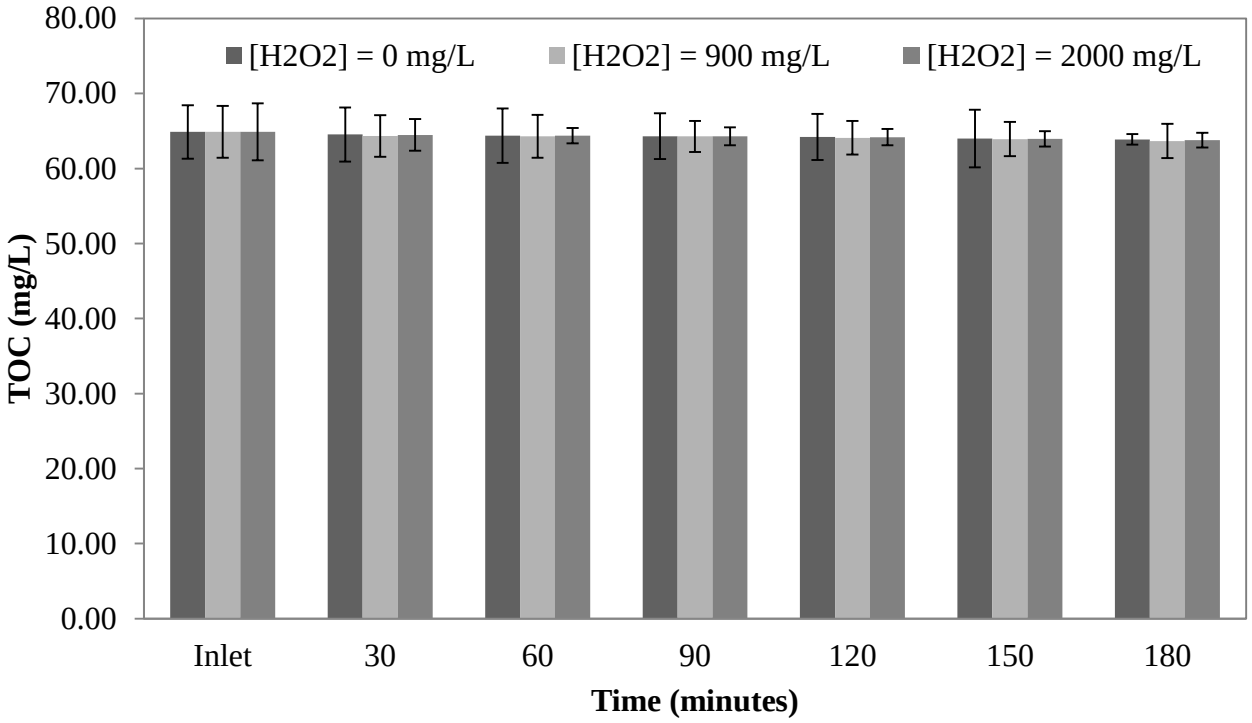


Figure 4.26. Dark experiments for TOC removal in raw SSWW for H_2O_2 concentrations of 0, 600, and 1200 mg/L (TOC_{in} = 64.88 mg/L) in the UV/H_2O_2 process alone in continuous mode without recycling.

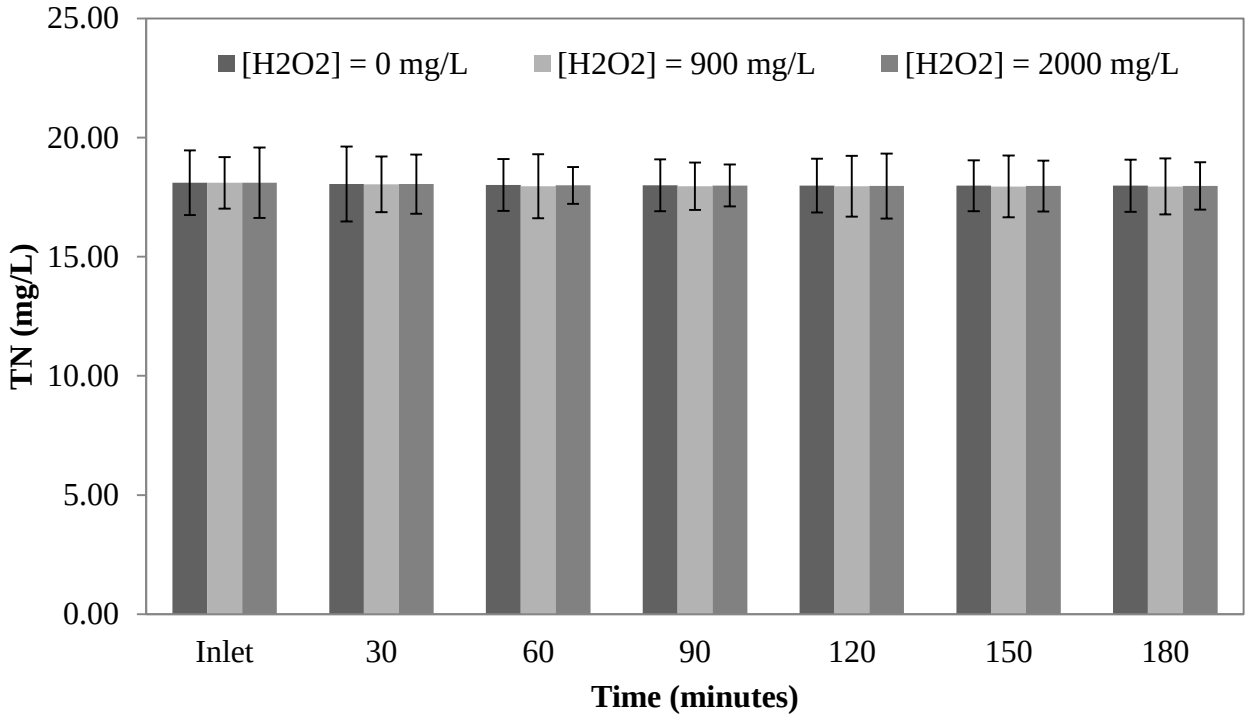


Figure 4.27. Dark experiments for TN removal in raw SSWW for H_2O_2 concentrations of 0, 600, and 1200 mg/L (TN_{in} = 18.10 mg/L) in the UV/H_2O_2 process alone in continuous mode without recycling.

In order to determine the optimum dosage of H_2O_2, different H_2O_2 concentrations were used (0, 100, 600, 900, 1200, 1500 and 2000 mg/L), and TOC concentrations varied from 64.88 to 349.84 mg/L for the experiments in batch recirculation mode. The results revealed a reasonable efficiency, up to 75.22% TOC removal rate, was obtained for an influent concentration of 64.88 mgTOC/L, HRT of 180 min, and H_2O_2 concentration of 900 mg/L, as depicted in Figure 4.28. Therefore, further experiments were conducted using 900 mg/L as the optimal dose for the treatment of SSWW. Besides, Figure 4.28 also confirms that at a higher slaughterhouse wastewater concentration, the TOC removal capacity decreased due to the presence of more organic matter ready to compete for hydroxyl radicals ($^{\bullet}OH$).

It is highly recommended to determine an optimal ratio of $[H_2O_2]/[TOC]$ (Tabrizi and Mehrvar, 2004; Cao, 2009; Cao and Mehrvar, 2011; Barrera, 2011; Barrera et al., 2011), which is a critical parameter for optimization of the wastewater treatment by adjusting the concentration of H_2O_2 to specific organic matter concentrations present at any time while the treatment is in progress. This factor helps to maximize the efficiency and reduce chemical and electrical costs. Furthermore, Figure 4.29 illustrates an optimum molar ratio dosage of 13.87 $mgH_2O_2/mgTOC_{in}$ for the UV/H_2O_2 process. These results are in accordance with the previous studies that propose optimum molar ratios in the range of 0-100 $mgH_2O_2/mgTOC_{in}$ (Baeza et al., 2003; Torrades et al., 2003; Tabrizi and Mehrvar, 2004; Pagano et al., 2008; Cao, 2009; Cao and Mehrvar, 2011; Barrera, 2011; Barrera et al., 2011).

Likewise, the ratios of H_2O_2 concentration by influent TOC concentration and HRTs within the UV/H_2O_2 process in batch recirculation mode are depicted in Figure 4.30, where an optimum ratio of 4.62 $mgH_2O_2/mgTOC_{in}$.h was found to result a maximum TOC removal of 75.22%.

4.6. TOC and TN removal in SSWW using combined anaerobic-aerobic and UV/H_2O_2 processes

Previous sections have shown the high efficiency of different alternatives for treating slaughterhouse wastewater (SSWW). However, the performance of the combination of all those processes in order to get complete mineralization of the organic matter was studied.

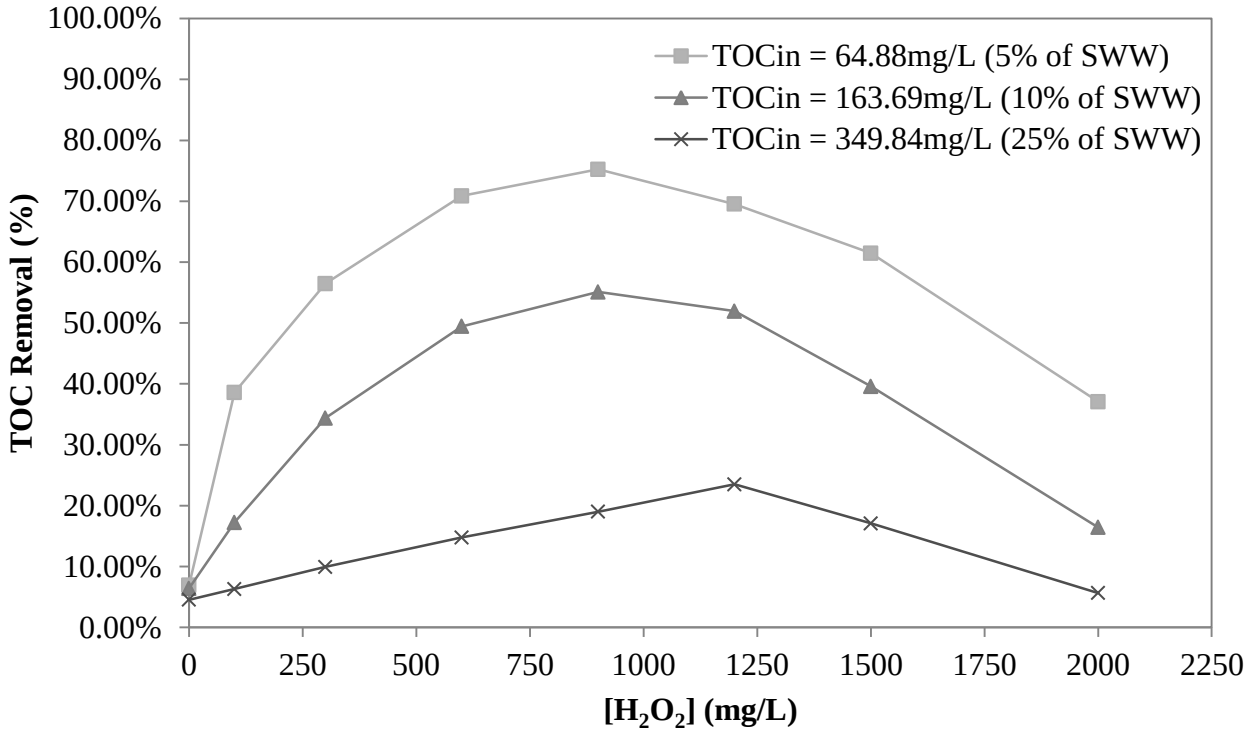


Figure 4.28. Optimal concentration of H_2O_2 for TOC removal in different SSWW concentrations, within the UV/H_2O_2 process in batch recirculation mode.

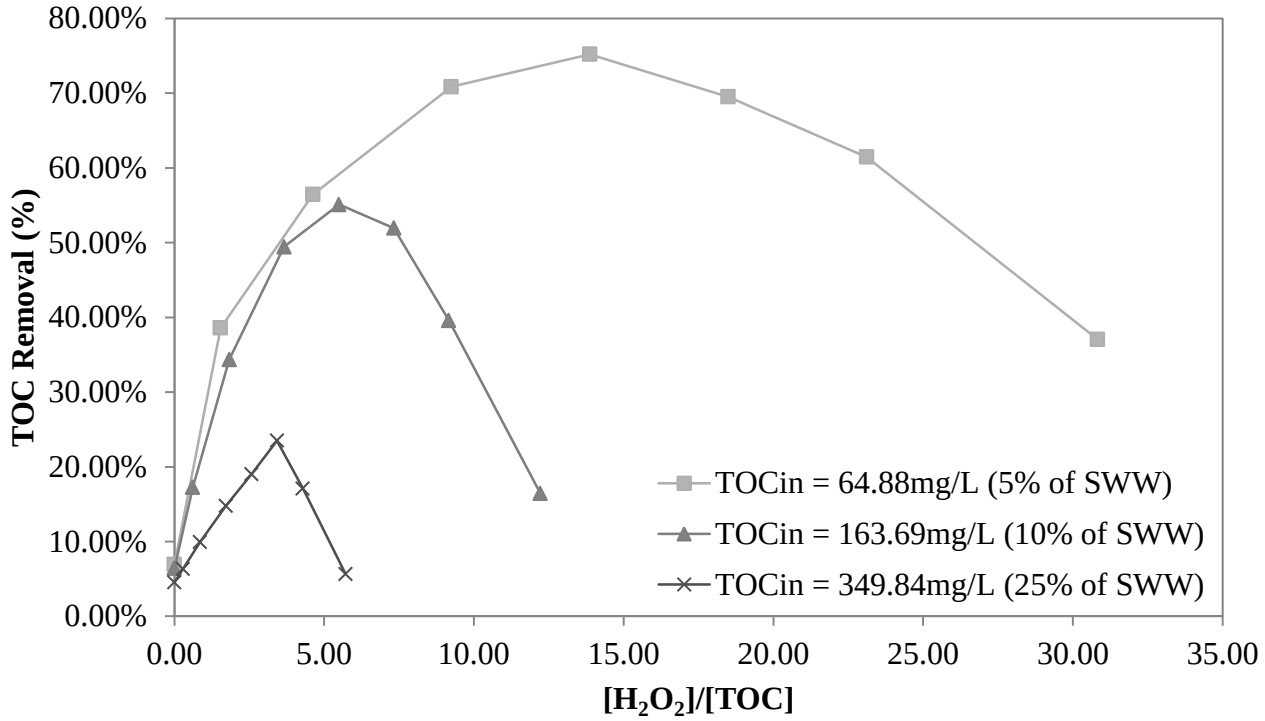


Figure 4.29. Relation of molar ratio of $[H_2O_2]/[TOC]$ for different SSWW concentrations within the UV/H_2O_2 process in batch recirculation mode.

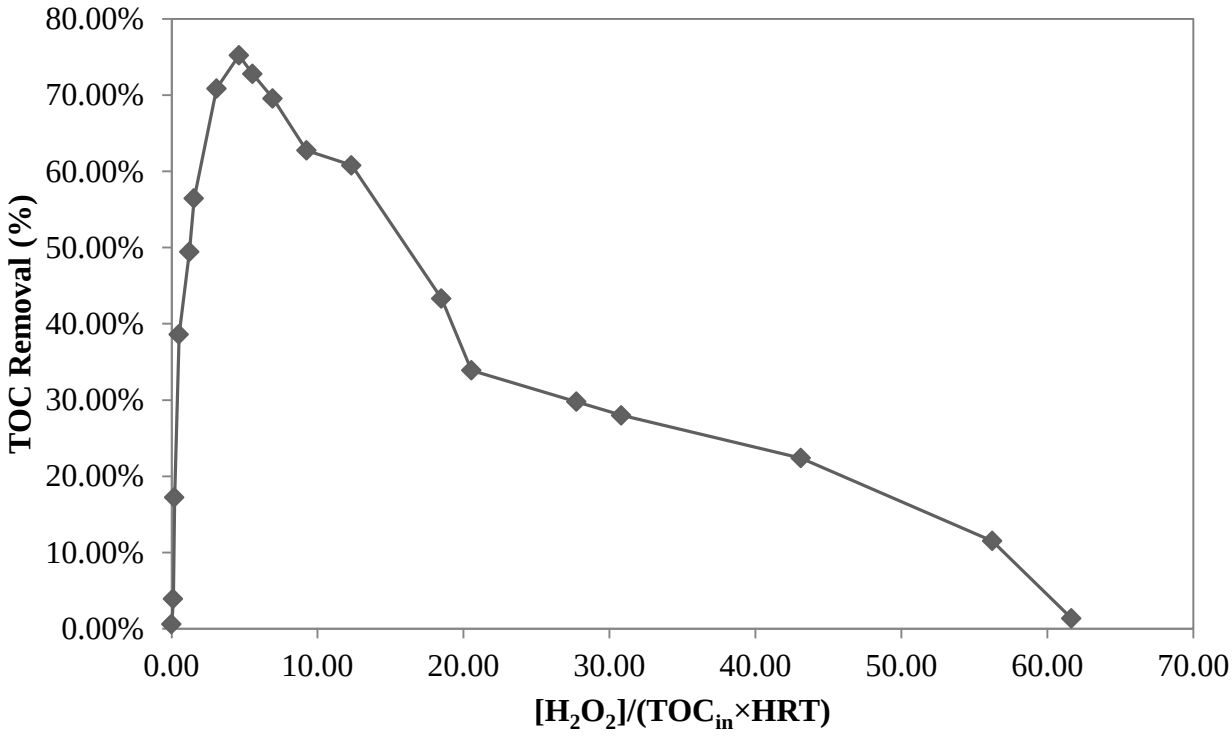


Figure 4.30. Relation of molar ratio of $[H_2O_2]/[TOC_{in} \times HRT]$ for different TOC removals within the UV/H_2O_2 process in batch recirculation mode

Figures 4.31 and 4.32 show the TOC and TN concentrations of the SSWW during different stages of combined ABR-aerobic AS-UV/H_2O_2 processes at HRTs of 3.15 to 4 days and flow rates of 5.90 to 7.50 mL/min with influent TOC and TN concentrations of 941.19–1006.90 and 200.03–214.08 mg/L, respectively. Up to 99.98% TOC removal and 82.84% TN removal rates were obtained for influent concentrations of 1,004.88 mgTOC/L and 200.03 mgTN/L, HRT of 4.00 days, and a flow rate of 5.90 mL/min (Figures 4.33 and 4.34). Other experiments show 99.13% TOC and 82.51% TN removal rates, obtained for an influent concentration of 1,006.90 mgTOC/L and 203.84 mgTN/L, HRT of 3.50 days, and flow rate of 6.75mL/min. Likewise, up to 98.91% TOC and 81.03% TN removal rates were obtained for an influent concentration of 941.19 mgTOC/L and 214.08 mgTN/L, HRT of 3.15 days, and flow rate of 7.50mL/min as depicted in Figures 4.33 and 4.34.

These results confirm that an adequate combination of anaerobic and aerobic processes is essential for the nitrogen removal in order to obtain removal rates of more than 70% (up to 82.84% of TN removed) and they also confirm that using advanced oxidation processes as post-treatment guarantees the complete mineralization of the organic matter and disinfection of SSWW, with up to 99.98% of TOC removed as depicted in Figure 4.33 (Del Pozo and Diez, 2003; Ahn et al., 2007; Liu et al., 2008; Cao, 2009; Chan et al., 2009; Cao and Mehrvar, 2011; Barrera, 2011; Barrera et al., 2011).

Figures 4.35 and 4.36 show a comparison of all processes used in this study, with maximum TOC and TN removals reached by the different alternatives, including the UV/H_2O_2 process alone (75.22% for TOC and 5.99% for TN), the ABR process alone (89.47% for TOC and 49.68% for TN), the aerobic AS process alone (94.53% for TOC and 73.46% for TN), combined aerobic-anaerobic processes (96.10% for TOC and 76.44% for TN), combined anaerobic-aerobic processes (96.36% for TOC and 80.53% for TN), and combined anaerobic-aerobic and UV/H_2O_2 (99.98% for TOC and 82.84% for TN).

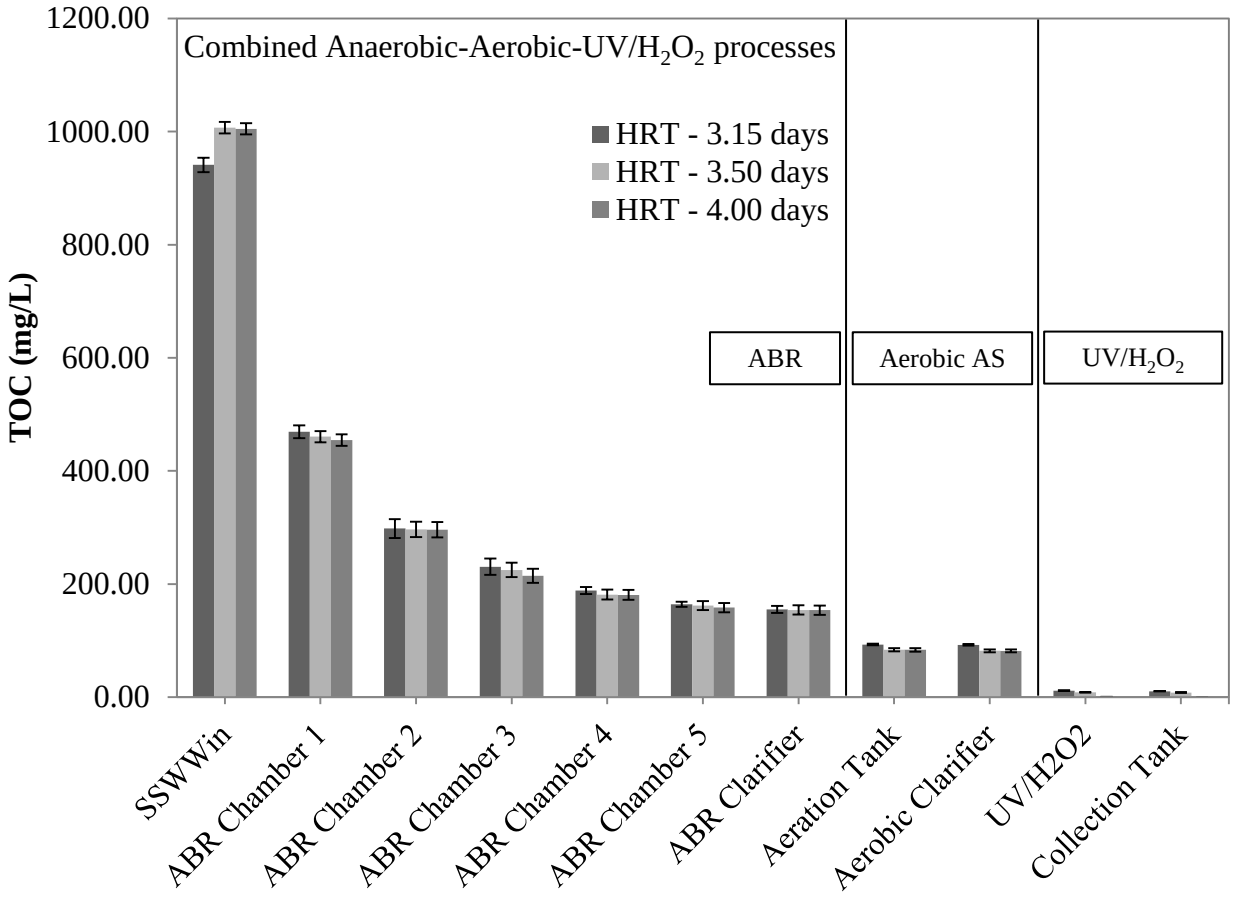


Figure 4.31. TOC removal in SSWW using combined anaerobic-aerobic-UV/H_2O_2 processes at different HRTs in continuous mode without recycling. Error bars represent standard deviations.

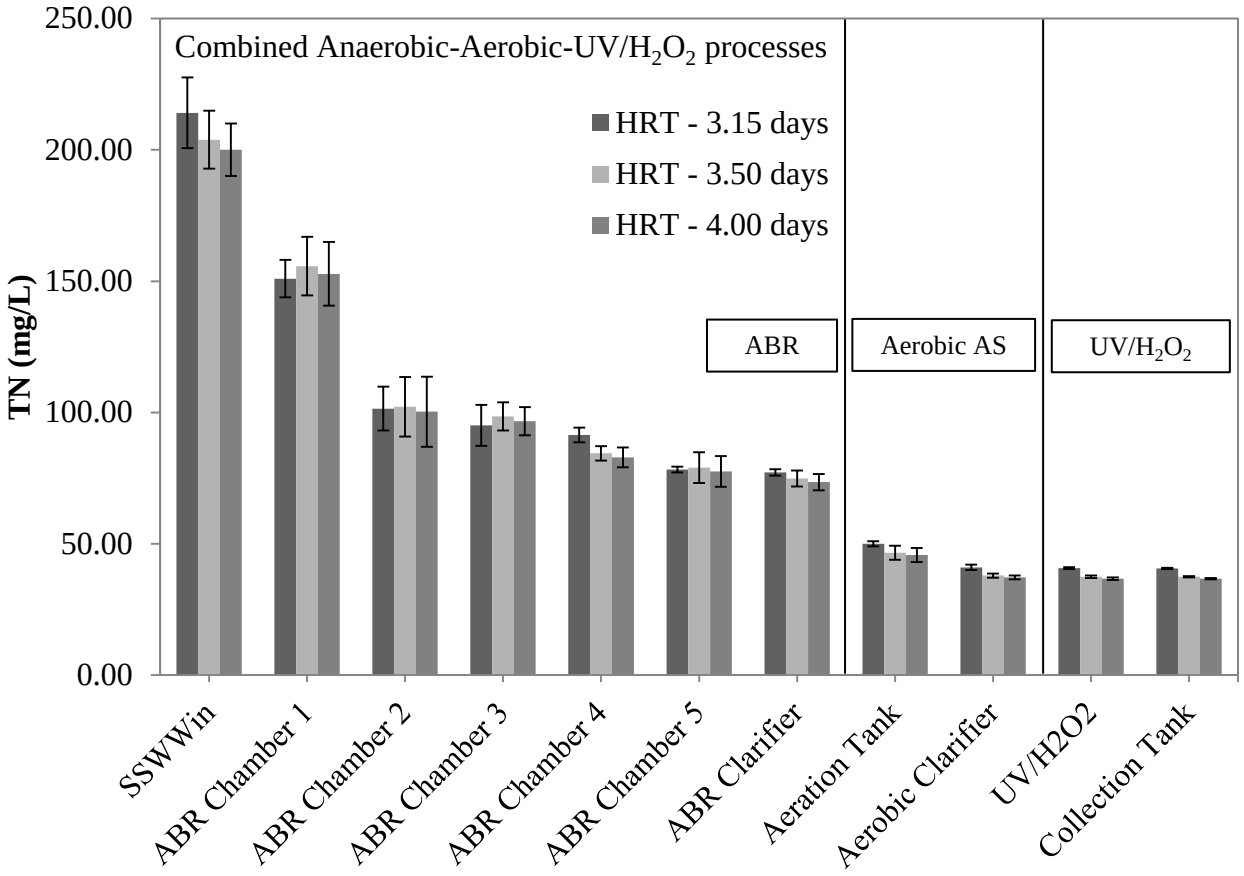


Figure 4.32. TN removal in SSWW using combined anaerobic-aerobic-UV/H_2O_2 processes at different HRTs in continuous mode without recycling. Error bars represent standard deviations.

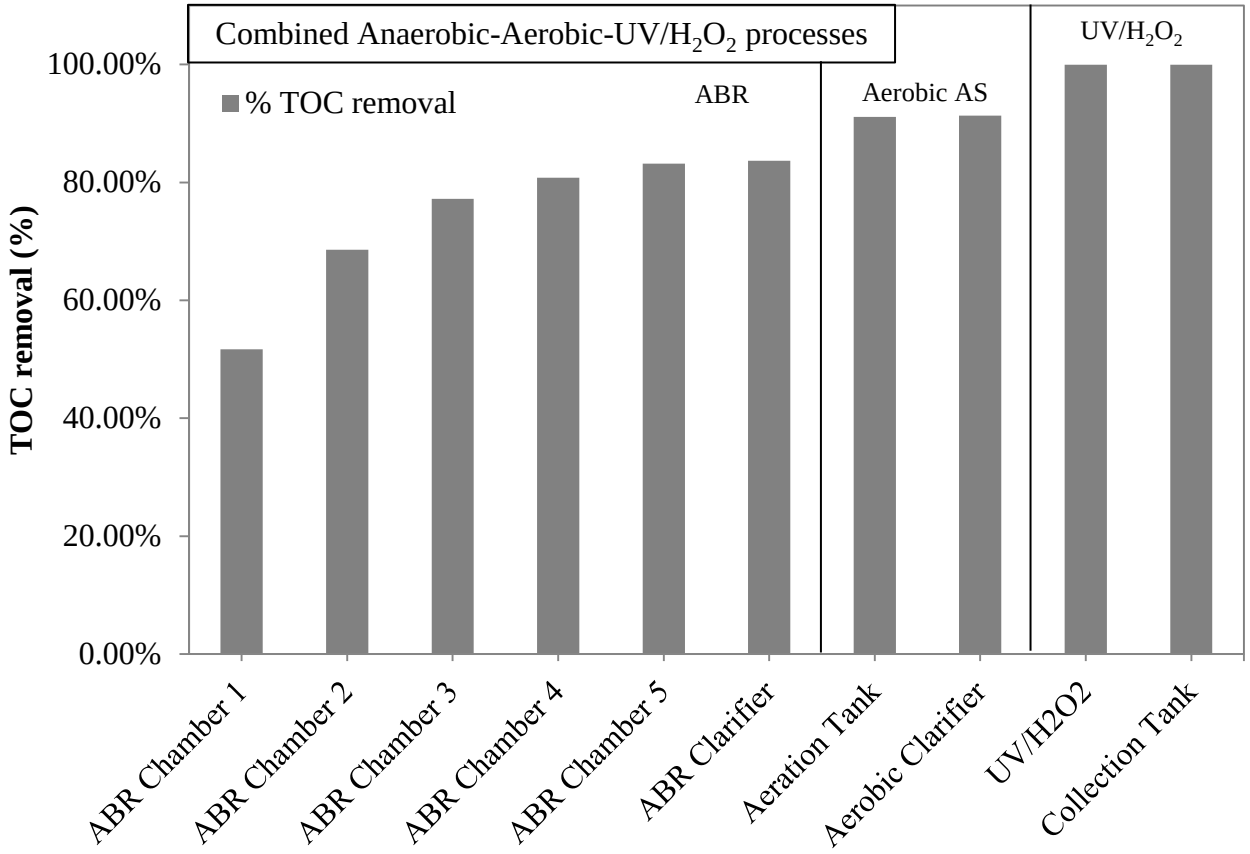


Figure 4.33. Maximum values on TOC removal in SSWW using combined anaerobic-aerobic-UV/H_2O_2 processes in continuous mode without recycling.

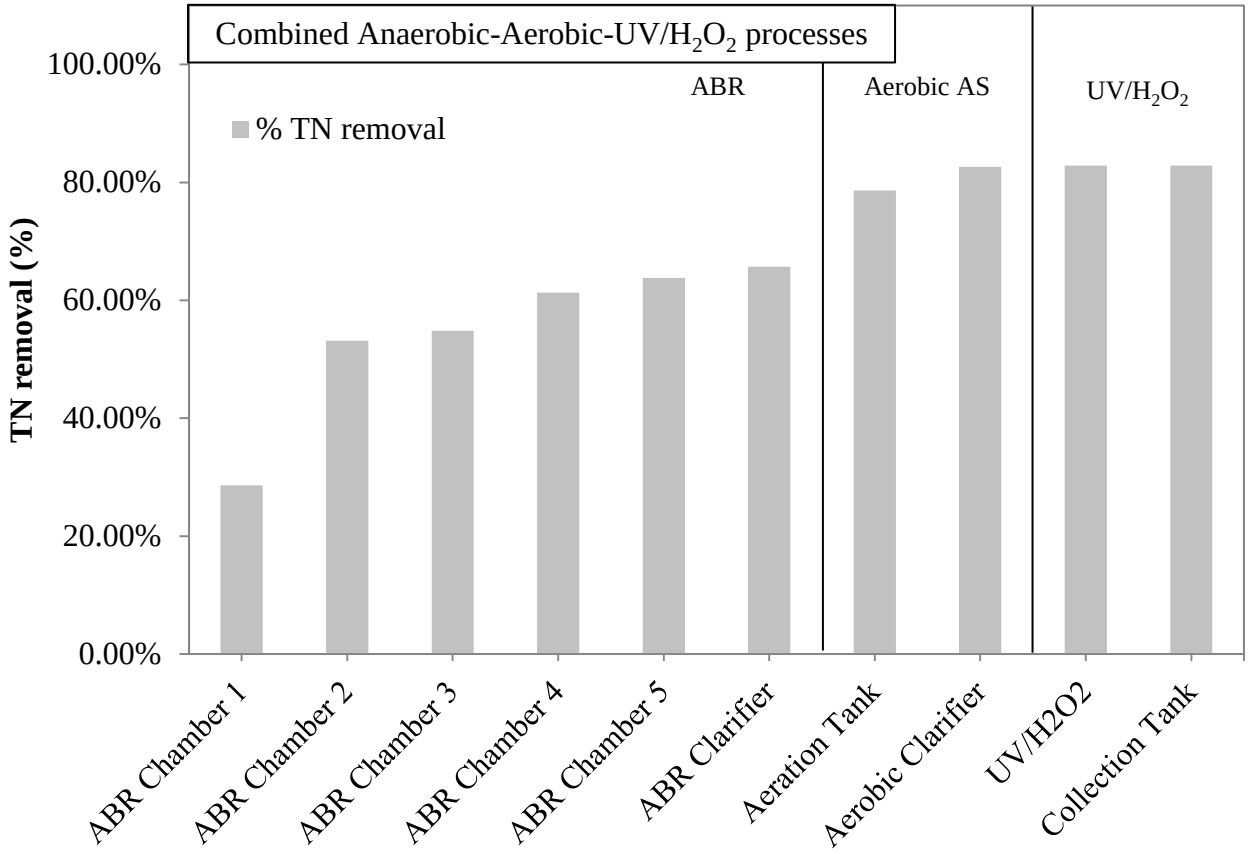


Figure 4.34. Maximum values on TN removal in SSWW using combined anaerobic-aerobic-UV/H_2O_2 processes in continuous mode without recycling.

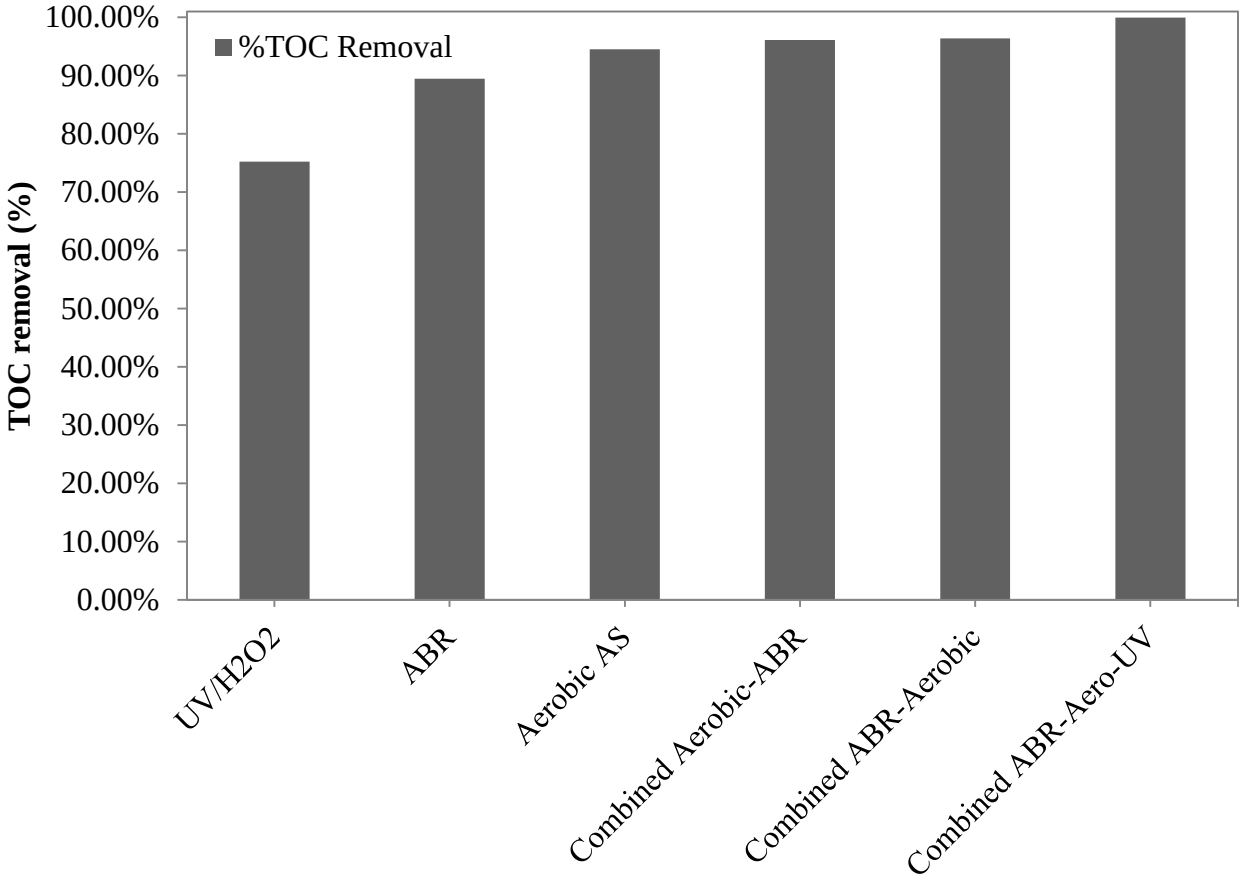


Figure 4.35. Comparison of TOC removal using different alternatives in continuous mode without recycling, including UV/H_2O_2 process alone, ABR process alone, aerobic AS process alone, combined anaerobic-aerobic processes, combined aerobic-anaerobic processes, and combined anaerobic-aerobic and UV/H_2O_2.

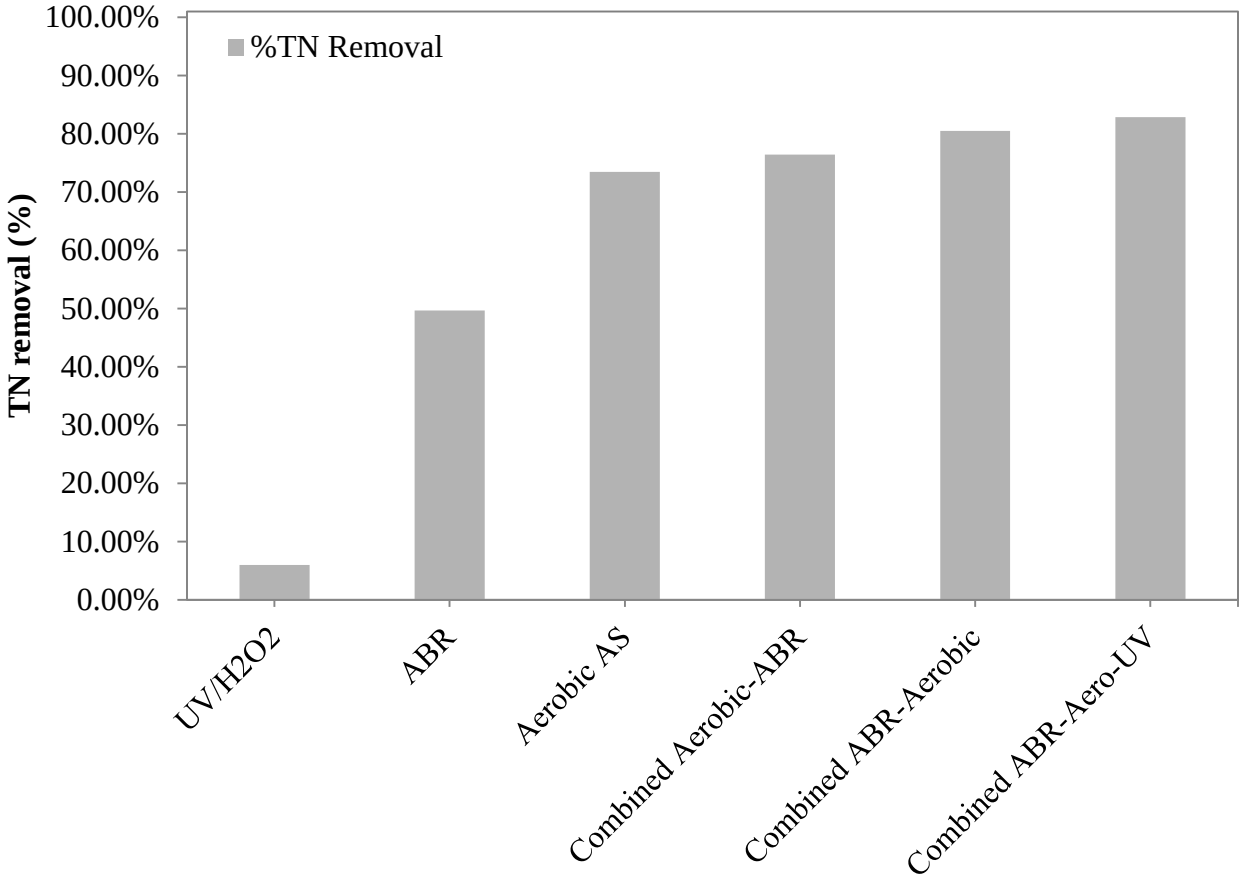


Figure 4.36. Comparison of TN removal using different alternatives in continuous mode without recycling, including UV/H_2O_2 process alone, ABR process alone, aerobic AS process alone, combined anaerobic-aerobic processes, combined aerobic-anaerobic processes, and combined anaerobic-aerobic and UV/H_2O_2.

4.7. $CBOD_5$ removal in SSWW using ABR alone, aerobic AS alone, UV/H_2O_2 alone, and combined processes

Figures 4.37 and 4.38 show there was a significant reduction in $CBOD_5$ using ABR alone, aerobic AS alone, UV/H_2O_2 alone, and combined processes. Figure 4.37 shows the maximum inlet concentration of $CBOD_5$ from the SSWW to be 640 mg/L. It also illustrates the $CBOD_5$ concentration of every effluent of the different processes used for the treatment of SSWW, including UV/H_2O_2 alone (100mg/L); aerobic AS alone (50 mg/L); ABR alone (31 mg/L); combined anaerobic-aerobic processes (4 mg/L); combined aerobic-anaerobic processes (3 mg/L); and combined anaerobic-aerobic and UV/H_2O_2 (2 mg/L), where error bars represent standard deviations. In addition, Figure 4.38 illustrates that the maximum removal efficiency of $CBOD_5$ was reached using combined anaerobic-aerobic and UV/H_2O_2 processes; up to 99.69%. Comparatively, the maximum $CBOD_5$ removal efficiencies for other methods, including UV/H_2O_2 alone, aerobic AS alone, ABR alone, combined anaerobic-aerobic processes, and combined aerobic-anaerobic processes, reached 84.38, 92.19, 95.16, 99.38 and 99.53% of removal, respectively. It was deduced that only by using biological treatment the $CBOD_5$ concentration could be reduced more than 90% since maximum $CBOD_5$ removal by using UV/H_2O_2 alone merely was reached to 84.38% at a H_2O_2 concentration of 900 mg/L and a HRT of 3 h.

As depicted in Figure 4.39, TOC is directly proportional to $CBOD_5$. This confirms that TOC analysis provides an accurate appraisal of the total organic compounds present in a wastewater sample in comparison to BOD or COD. TOC can be quantified by measuring the CO_2 generated when the organic compounds are oxidized. Thus, TOC analysis excludes the inorganic carbon compounds in order to obtain accurate results of the organic contamination in source water. As the American Public Health Association (APHA) described, TOC method may be more suitable for determining organic matter content since it takes into account all of its different oxidation states (APHA, 1998). Moreover, COD and BOD tests may take from 3 h to 5 days to produce any result, whereas TOC analysis can provide results in 15 min.

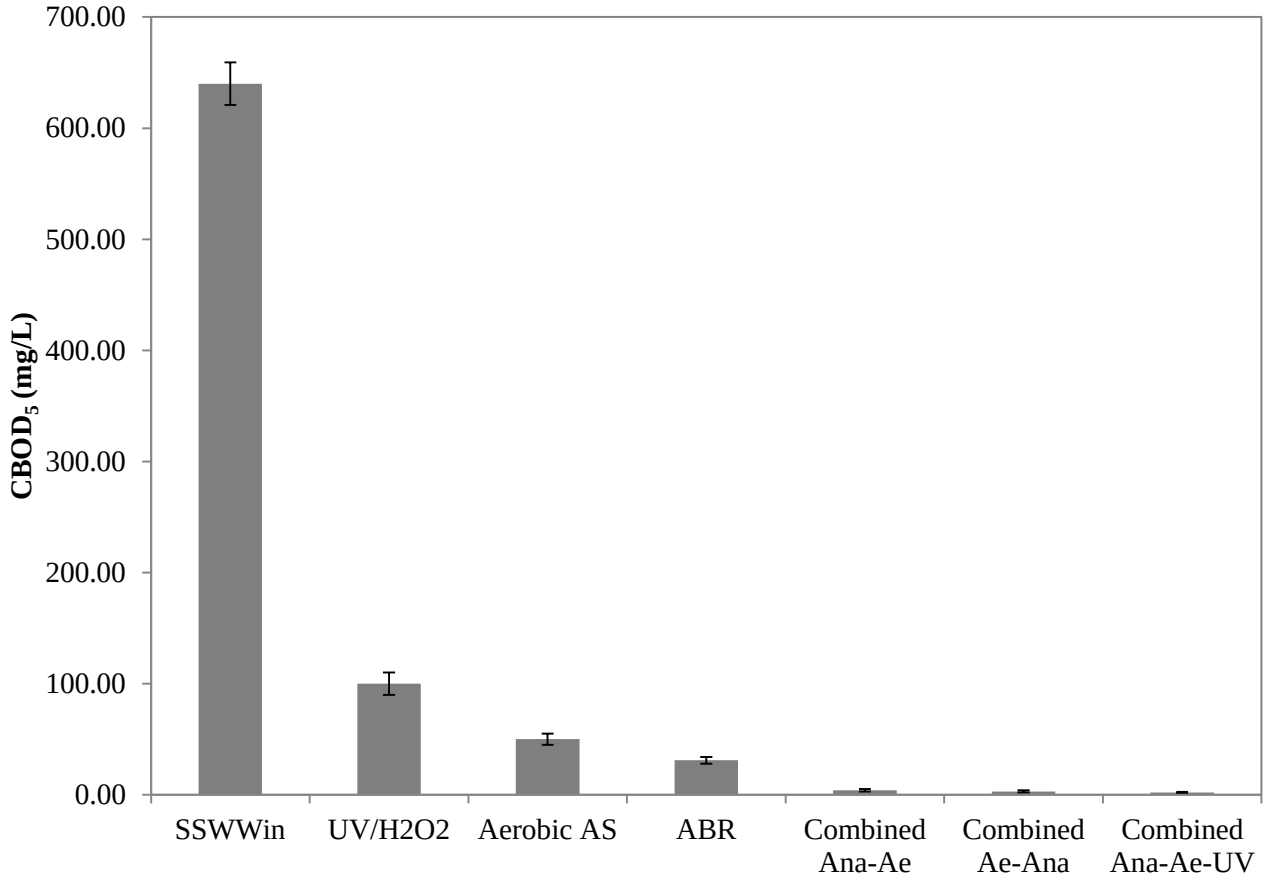


Figure 4.37. $CBOD_5$ concentration profile for different SSWW effluents from different processes in continuous mode without recycling, including UV/H_2O_2 process alone, ABR process alone, aerobic AS process alone, combined anaerobic-aerobic processes, combined aerobic-anaerobic processes, and combined anaerobic-aerobic and UV/H_2O_2. Error bars represent standard deviations.

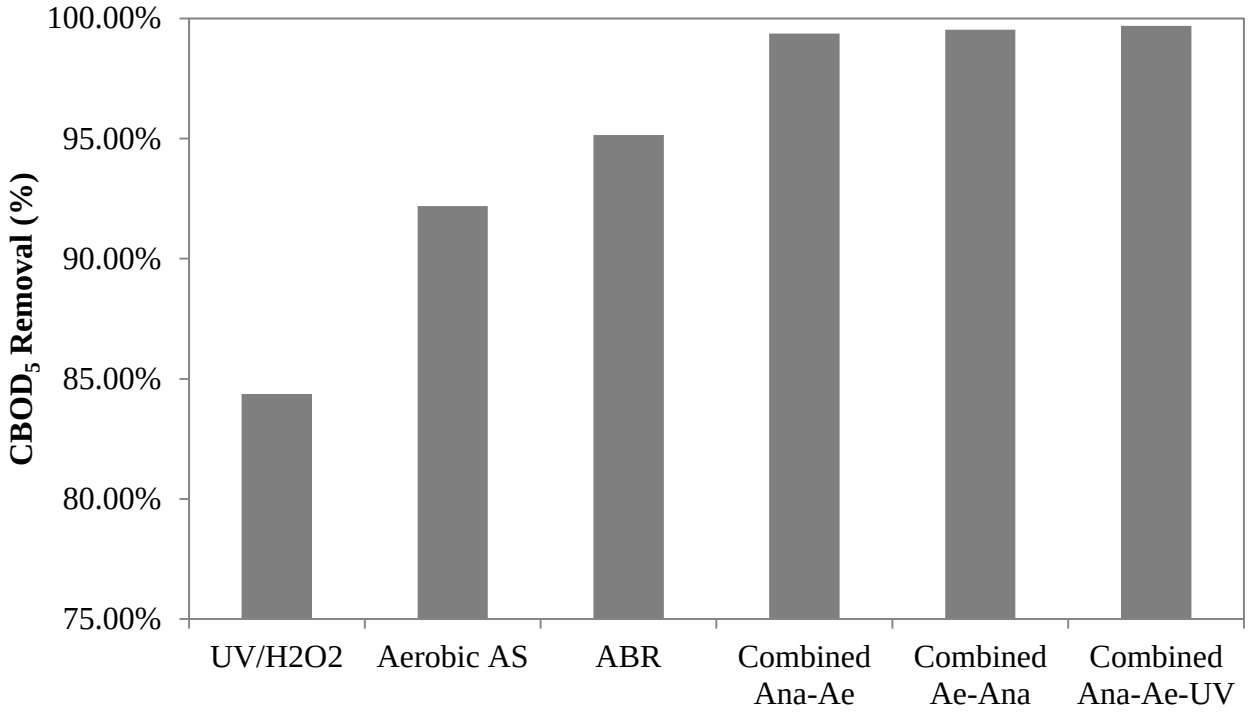


Figure 4.38. $CBOD_5$ removal in SSWW using different alternatives in continuous mode without recycling, including UV/H_2O_2 process alone, ABR process alone, aerobic AS process alone, combined anaerobic-aerobic processes, combined aerobic-anaerobic processes, and combined anaerobic-aerobic and UV/H_2O_2.

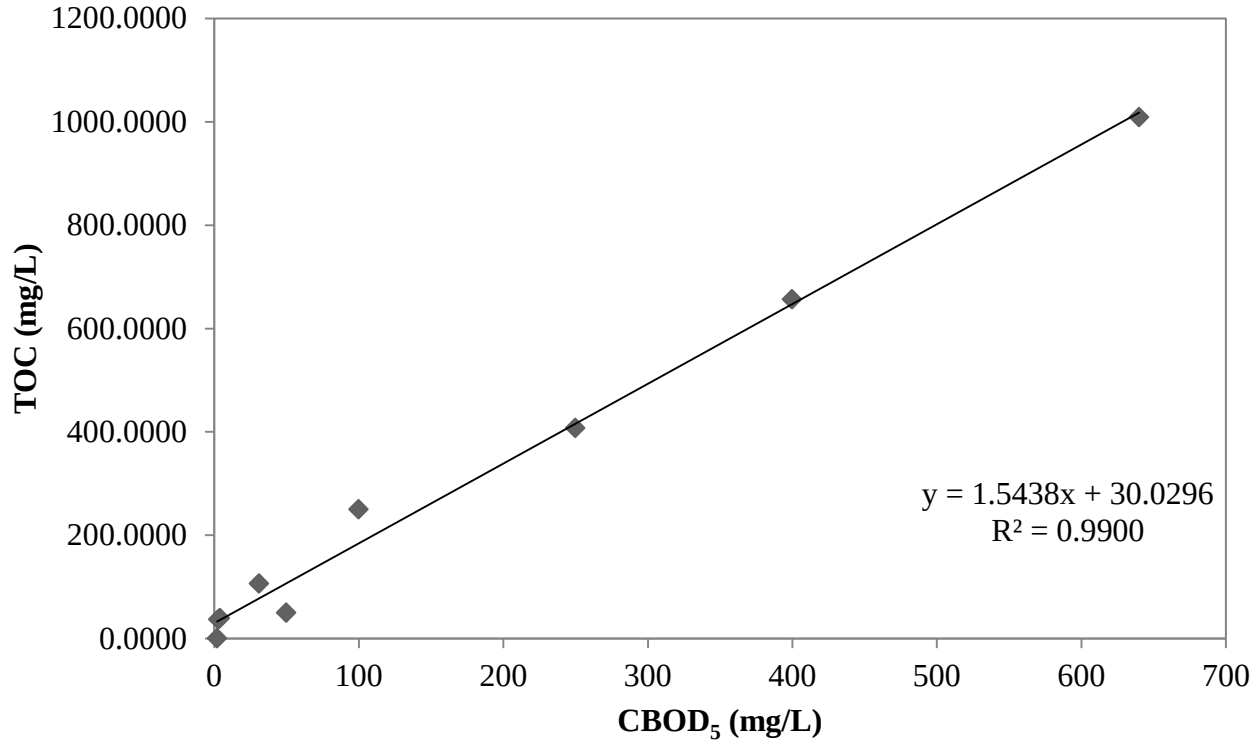


Figure 4.39. Correlation between $CBOD_5$ and TOC in SSWW using different alternatives in continuous mode without recycling, including UV/H_2O_2 process alone, ABR process alone, aerobic AS process alone, combined anaerobic-aerobic processes, combined aerobic-anaerobic processes, and combined anaerobic-aerobic and UV/H_2O_2.

4.8. Cost-effectiveness analysis (CEA) to determine the best alternative on SSWW treatment by optimizing total electricity cost and HRT

As described above, several processes were examined in order to determine their efficiencies in the treatment of SSWW, to evaluate the performance of the different configurations of the combined processes, and to analyze the factors affecting their effectiveness.

Several parameters are important for a wastewater treatment system, such as HRT, which will affect the final removal efficiency of organic pollutants in wastewater and the operating and maintenance (O&M) costs of the system; that is the reason why this parameter is necessary to be optimized. Therefore, at a laboratory scale, factors that affect the efficiency of the system are electricity consumption and the usage of chemicals such as H_2O_2 as fundamental parts of the total cost. Thus, these factors (electricity and H_2O_2 consumption) were considered for the CEA in this study in order to optimize the combined processes.

4.8.1. Kinetic modeling for the ABR alone

The kinetic model Equation (2.14) developed by Kennedy and Barriault (2007) describe the substrate concentration driving force within different compartments of an ABR without recycling. The first order rate constant could be calculated from operational treatment data knowing the substrate concentrations and biomass in each compartment. The mass balance in the first compartment and subsequent *i* compartments of an *n*-compartment ABR are shown as follows:

$$S_i = \frac{S_{i-1}}{(1+k_{Ci}X_iV_i/Q)} = \frac{S_{i-1}}{(1+k_{Ci}X_iV_it/V)} \quad \text{(for } i \geq 1\text{)} \qquad (2.14)$$

where,

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

S_{i-1} = concentration of the substrate in compartment $i-1$ of the ABR, when $i-1=0$ then $S_{i-1} = S_o$ (mg/L);

S_o = concentration of the substrate in the influent (mg/L);

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

r_r = recycle rate in the ABR, which is a percent of the flow rate of the influent (%);

k_{Ci} = first order rate coefficient of substrate in compartment *i* of the ABR;

k_{C1} = first order rate coefficient of substrate in compartment 1 of the ABR;

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

V_i = volume of the compartment *i* of the ABR (L);

Q = flow rate of influent = V/t (L/d);

V = total volume of the reactor (L); and

t = HRT (d).

$$S_1 = \frac{S_0}{(1+k_1X_1V_1t/V)} = \frac{S_0}{(1+(3.9857\times10^{-5})(13{,}325)(6.74)t/33.7)} \therefore S_1 = \frac{S_0}{(1+0.1062\mathrm{t})} \quad (4.1)$$

$$S_2 = \frac{S_1}{(1+k_2X_2V_2t/V)} = \frac{S_1}{(1+(2.3241\times10^{-5})(11{,}550)(6.74)t/33.7)} \therefore S_2 = \frac{S_1}{(1+0.0537\mathrm{t})} \quad (4.2)$$

$$S_3 = \frac{S_2}{(1+k_3X_3V_3t/V)} = \frac{S_2}{(1+(1.1643\times10^{-5})(16{,}150)(6.74)t/33.7)} \therefore S_3 = \frac{S_2}{(1+0.0376\mathrm{t})} \quad (4.3)$$

$$S_4 = \frac{S_3}{(1+k_4X_4V_4t/V)} = \frac{S_3}{(1+(1.5527\times10^{-5})(10{,}600)(6.74)t/33.7)} \therefore S_4 = \frac{S_3}{(1+0.0329\mathrm{t})} \quad (4.4)$$

$$S_5 = \frac{S_4}{(1+k_5X_5V_5t/V)} = \frac{S_4}{(1+(9.3321\times10^{-5})(11{,}833)(6.74)t/33.7)} \therefore S_5 = \frac{S_4}{(1+0.2209\mathrm{t})} \quad (4.5)$$

Since there is no recycling, $S_5 = S_f$, and Equations (4.1) to (4.5) are reduced to Equations (4.6) and (4.7), which are used to predict the effluent concentrations of TOC in the ABR.

$$S_f = \frac{[(\{[S_0/(1+8.98\times10^4k_1\mathrm{t/V})]/(1+7.78\times10^4k_2\mathrm{t/V})\}/(1+1.09\times10^5k_3\mathrm{t/V}))/(1+7.14\times10^4k_4\mathrm{t/V})]}{(1+7.98\times10^4k_5\mathrm{t/V})} \quad (4.6)$$

$$S_f = \frac{[(\{[S_0/(1+0.1062\mathrm{t})]/(1+0.0537\mathrm{t})\}/(1+0.0376\mathrm{t}))/(1+0.0329\mathrm{t})]}{(1+0.2209\mathrm{t})} \quad (4.7)$$

The comparison between predicted values and the experimental data is presented in Figure 4.40, which shows an agreement between the predicted model values and the experimental data. Therefore, Equation (4.7) could be used to predict the effluent TOC concentration at a specific HRT for the ABR process alone.

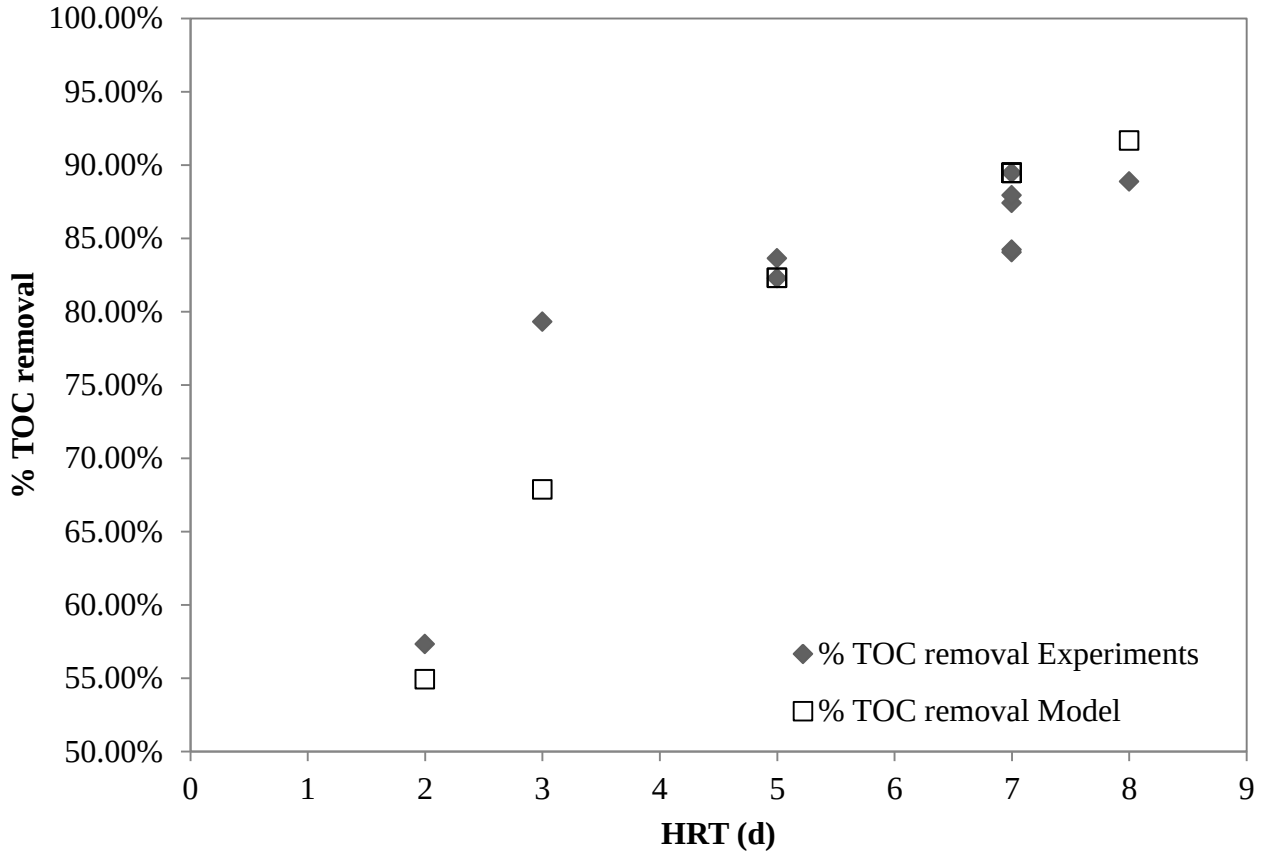


Figure 4.40. TOC removal comparison of the predicted values using Equation (4.7) and the experimental data of the SSWW treatment using ABR process alone in continuous mode without recycling.

4.8.2. Kinetic modeling for the aerobic AS alone

The kinetic model Equation (4.8) developed by Reynolds and Yang (1966) for the completely mixed activated sludge process is based on growth relationships and material balances on the substrate and. biological cell mass. This equation was used to predict the effluent concentrations of TOC in the aerobic AS reactor.

$$t = \frac{S_0 - S_f}{K\bar{X}S_f} \tag{4.8}$$

where,

t = HRT (d);

S_o = concentration of the substrate in the influent (mg/L);

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

K = first order rate coefficient of substrate; and

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

Equation (4.8) may be rearranged as follows (Reynolds and Richards, 1996):

$$\frac{S_0 - S_f}{\bar{X}t} = KS_f \tag{4.9}$$

$$S_f = \frac{S_0}{(1+K\bar{X}t)} \tag{4.10}$$

then,

$$S_f = \frac{S_0}{(1+2{,}399Kt)} \tag{4.11}$$

$$S_f = \frac{S_0}{(1+(2{,}399)(1.0283\times10^{-3})t)} \therefore S_f = \frac{S_0}{(1+2.4669t)} \tag{4.12}$$

The comparison between predicted values and the experimental data is presented in Figure 4.41, which shows an agreement between the predicted model values and the experimental data. Therefore, Equation (4.12) could be used to predict the effluent TOC concentration at a specific HRT for the aerobic AS process alone.

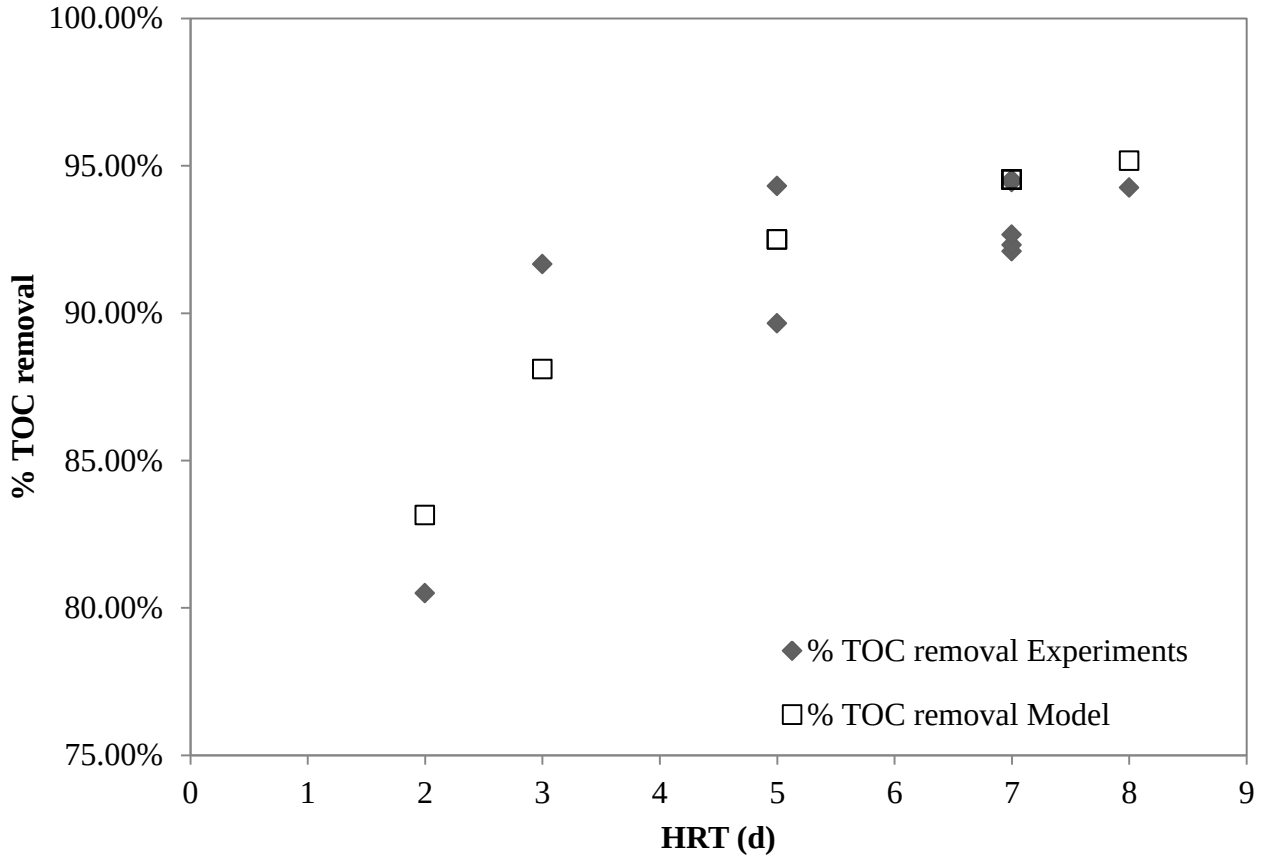


Figure 4.41. TOC removal comparison of the predicted values using Equation (4.12) and the experimental data of the SSWW treatment using aerobic AS process alone in continuous mode without recycling.

4.8.3. Kinetic modeling for the combined anaerobic-aerobic processes

For the combined biological processes, two equations were developed by combining Equations (4.6) and (4.11) as shown below. For combined anaerobic-aerobic processes, Equation (4.6) is substituted in Equation (4.11) because the effluent of the ABR process becomes the influent of the aerobic AS process.

$$S_f = \frac{\left(\frac{[(\{[S_0/(1+8.98\times10^4 k_1 \mathrm{t/V})]/(1+7.78\times10^4 k_2 \mathrm{t/V})\}/(1+1.09\times10^5 k_3 \mathrm{t/V}))/(1+7.14\times10^4 k_4 \mathrm{t/V})]}{(1+7.98\times10^4 k_5 \mathrm{t/V})}\right)}{(1+2{,}399Kt)} \quad (4.13)$$

then,

$$S_f = \frac{[(\{[S_0/(1+0.1895t)]/(1+0.0269t)\}/(1+0.0278t))/(1+0.0168t)]/(1+0.1412t)}{(1+0.5505t)} \quad (4.14)$$

For combined aerobic-anaerobic processes, Equation (4.11) is substituted into Equation (4.6), because the effluent of the aerobic AS process becomes the influent of the ABR process.

$$S_f = \frac{[(\{[\{S_0/(1+2{,}399Kt)\}/(1+8.98\times10^4 k_1 \mathrm{t/V})]/(1+7.78\times10^4 k_2 \mathrm{t/V})\}/(1+1.09\times10^5 k_3 \mathrm{t/V}))/(1+7.14\times10^4 k_4 \mathrm{t/V})]}{(1+7.98\times10^4 k_5 \mathrm{t/V})} \quad (4.15)$$

then,

$$S_f = \frac{[(\{[\{S_0/(1+0.7974t)\}/(1+0.0185\mathrm{t})]/(1+0.0021\mathrm{t})\}/(1+0.0784\mathrm{t}))/(1+0.1053\mathrm{t})]}{(1+0.0866\mathrm{t})} \quad (4.16)$$

Thus, Equation (4.14) was used to predict the effluent concentrations of TOC for the combined anaerobic-aerobic system and Equation (4.16) for the combined aerobic-anaerobic system.

The comparison between predicted values and the experimental data for the combined anaerobic-aerobic processes and combined aerobic-anaerobic processes are presented in Figures 4.42 and 4.43, respectively. These figures show an agreement between the predicted model values and the experimental data. Therefore, Equations (4.14) and (4.16) could be used to predict the effluent TOC concentrations at a specific HRT for the combined anaerobic-aerobic processes and combined aerobic-anaerobic processes, respectively.

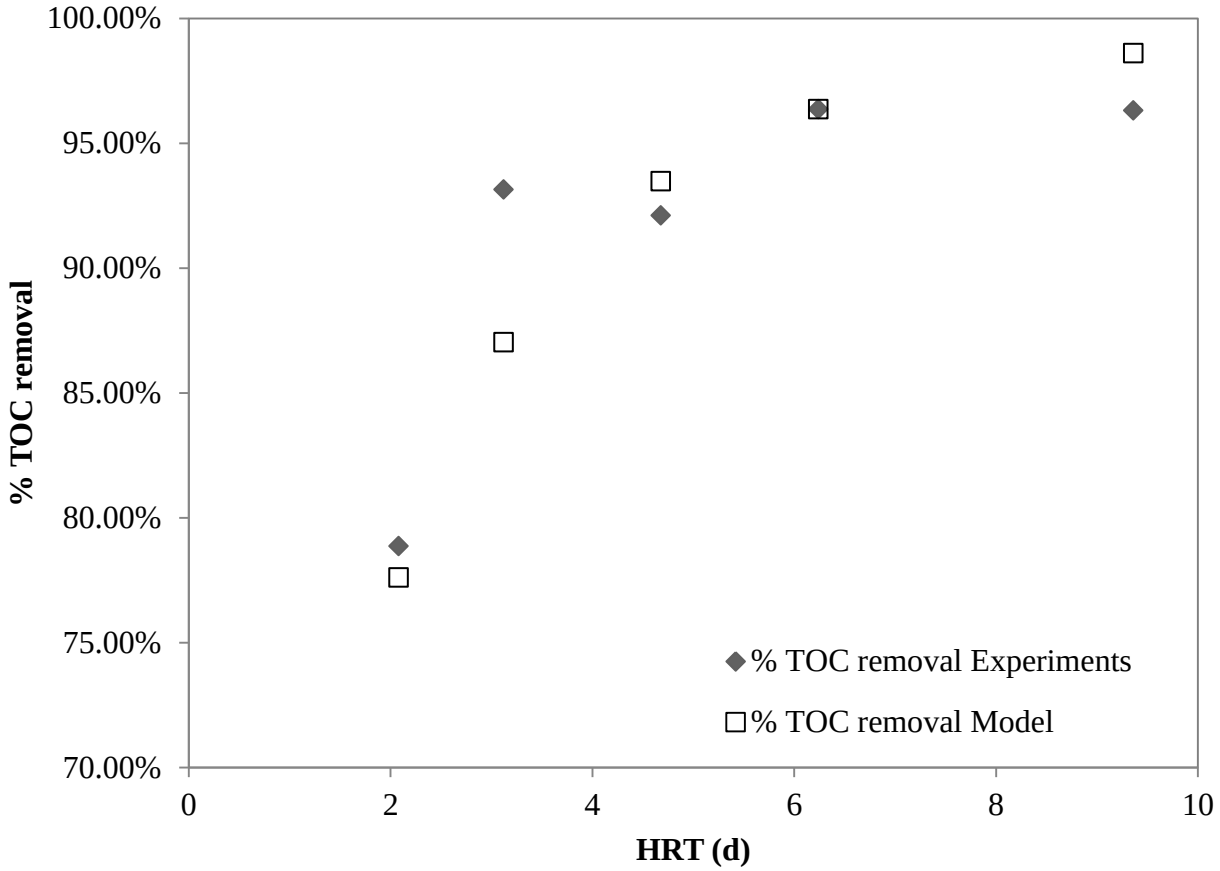


Figure 4.42. TOC removal comparison of the predicted values using Equation (4.14) and the experimental data of the SSWW treatment using combined anaerobic-aerobic processes in continuous mode without recycling.

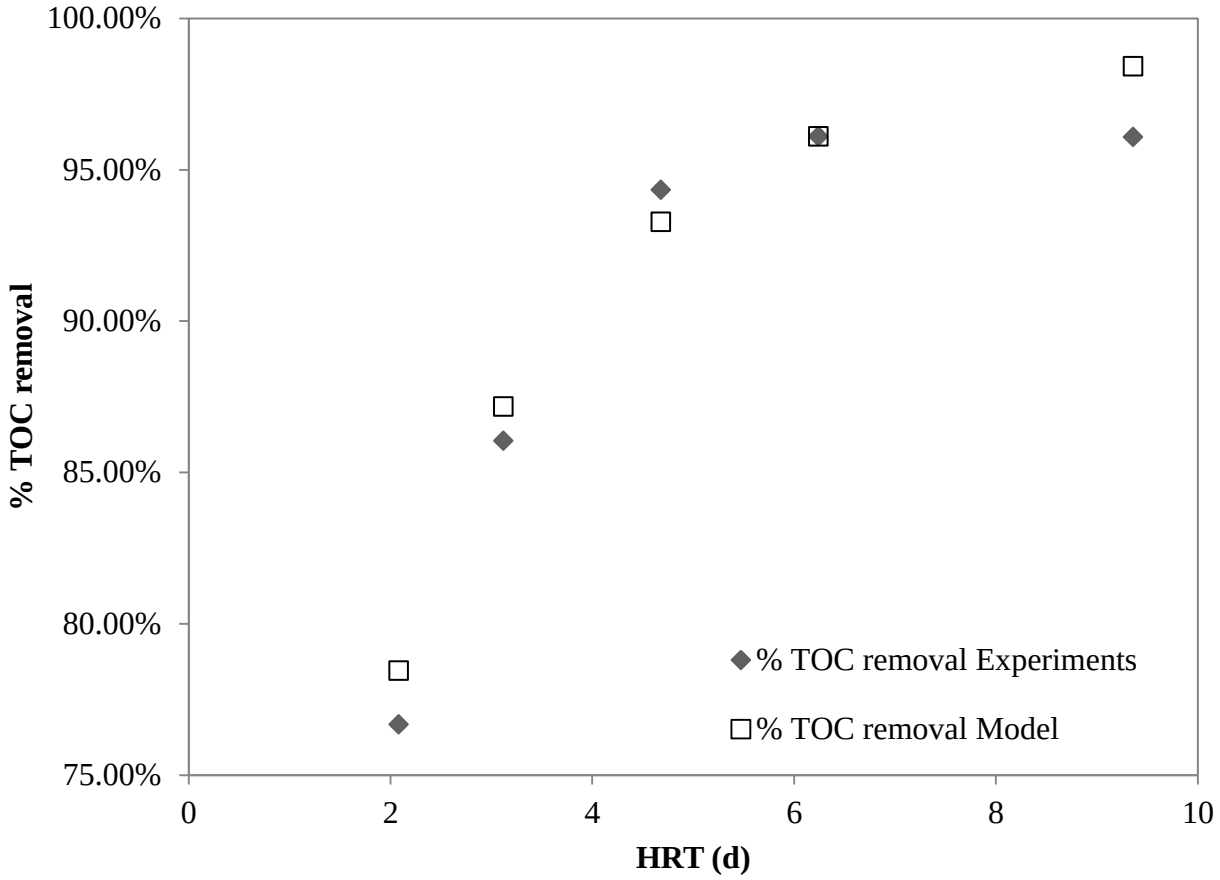


Figure 4.43. TOC removal comparison of the predicted values using Equation (4.16) and the experimental data of the SSWW treatment using combined aerobic-anaerobic processes in continuous mode without recycling.

4.8.3. Kinetic modeling for the UV/H_2O_2 process alone

According to Shemer et al. (2006), the quantum yield (ϕ) can be calculated by Equation (4.17) as shown below.

$$\phi[TOC] = \frac{-d[TOC]/dt}{k_{s(254\ nm)}} \tag{4.17}$$

where,

$k_{s(254\ nm)}$ = specific rate of light absorption by TOC at 254 nm (E/mol.s).

$k_{s(254\ nm)}$ can be calculated by Equation (4.18) as follows:

$$k_{s(254\ nm)} = \frac{q_{o(254\ nm)}\varepsilon_{(\lambda 254\ nm)}\left[1-10^{-\alpha_{(\lambda 254\ nm)}(r-R_i)}\right]}{\alpha_{(254\ nm)}(r-R_i)} \tag{4.18}$$

where,

$q_{o(254\ nm)}$ = incident photon irradiance at 254 nm (E/cm^2.s);

$\varepsilon_{(\lambda 254\ nm)}$ = molar absorption coefficient of TOC at 254 nm (1/M.cm);

$\alpha_{(254\ nm)}$ = absorption coefficient at 254 nm (1/cm);

r = photoreactor nominal radius (cm); and

R_i = photoreactor inner radius (cm).

Equation (4.17) can be rearranged and integrated as follows:

$$\phi k_{s(254\ nm)} dt = \frac{-d[TOC]}{[TOC]} \tag{4.18}$$

$$\int_{t_0}^{t_f} \phi k_{s(254\ nm)} dt = -\int_{TOC_0}^{TOC_f} \frac{d[TOC]}{[TOC]} \tag{4.19}$$

$$\phi k_{s(254\ nm)} t = \ln\left(\frac{[TOC_0]}{[TOC_f]}\right) \tag{4.20}$$

$$\phi = \frac{\ln\left(\frac{[TOC_0]}{[TOC_f]}\right)}{k_{s(254\ nm)}t} \tag{4.21}$$

Molar concentrations for TOC_o and TOC_f are calculated as follows:

$$[TOC_o] = (64.88\ mgTOC/L) \cdot \left(\frac{1\ mol\ TOC}{12{,}000\ mg\ TOC}\right) = 5.41 \times 10^{-3}\ moles\ TOC/L$$

$$[TOC_f] = (16.08\ mgTOC/L) \cdot \left(\frac{1\ mol\ TOC}{12{,}000\ mg\ TOC}\right) = 1.34 \times 10^{-3}\ moles\ TOC/L$$

According to Oppenländer (2003), the energy (*En*) of a single photon at 254 nm is calculated by Equation (4.22) as follows:

$$En_{(254\ nm)} = \frac{hc}{\lambda} \tag{4.22}$$

where,

h = Planck's constant (6.626×10^{-34} J.s);

c = speed of light (2.998×10^{8} m/s); and

λ = 254×10^{-9} m.

then,

$$En_{(254\ nm)} = \frac{(6.626 \times 10^{-34}\ \text{J.s})(2.998 \times 10^{8}\ \text{m/s})}{254 \times 10^{-9}\ m} = 7.82 \times 10^{-19}\ J/photon$$

Energy of one mole of photons can be calculated by using Avogadro's number (N_A):

$$En_{(254\ nm)} = (7.82 \times 10^{-19}\ J/photon) \cdot \frac{6.022 \times 10^{23} photons}{1\ mol\ photons} = 4.7097 \times 10^{5} J/moles\ photons$$

The energy (*En*) is used to calculate the incident light flux (q_o) by dividing the power of the UV lamp (14 W) by the surface area of the quartz sleeve (*S*) as follows:

$$S = 2\pi R_i L \tag{4.23}$$

thus,

$$S = 2\pi(1.25\ cm)(34\ cm) = 267.04\ cm^2$$

$$q_{o(254\ nm)} = \frac{14\ W}{267.04\ cm^2} \cdot \frac{1\frac{J}{s}}{1\ W} \cdot \frac{1\ mol\ of\ photons}{4.7097 \times 10^5\ J} = 1.1132 \times 10^{-7}\ \frac{moles\ photons}{cm^2 \cdot s}$$

The molar absorption coefficient ($\varepsilon_{TOC(254\ nm)}$) and the decadic absorption coefficient ($\alpha_{(254\ nm)}$) are calculated as follows,

$$\varepsilon_{TOC(254\ nm)} = \frac{\alpha_{(254\ nm)}}{[TOC_0]} = \frac{A_b}{[TOC_0]l} \tag{4.24}$$

where,

A_b = absorbance (0.120 at 254 nm from Barrera, 2011); and

l = path length (1cm).

then,

$$\varepsilon_{TOC(254\ nm)} = \frac{0.120}{(5.41 \times 10^{-3}\ moles\ TOC/L)(1\ cm)} = 22.19\ L/mol.cm$$

$$\alpha_{(254\ nm)} = \frac{A_b}{l} = \frac{0.120}{1\ cm} = 0.12/cm$$

Replacing values in Equation (4.18):

$$k_{s(254\ nm)} = \frac{(1.11\times10^{-7} moles\ photons/cm^2\cdot s)(22.19\ L/mol\cdot cm)\cdot\left(\frac{1{,}000 cm^3}{1\ L}\right)[1-10^{-(0.12/cm)(1.25\ cm)}]}{(0.12/cm)(1.25\ cm)}$$

$$k_{s(254\ nm)} = 4.8103 \times 10^{-3}\ \frac{moles\ photons}{moles\ TOC \cdot s}$$

Replacing values in Equation (4.21), the quantum yield (ϕ) for the TOC photodegradation at 254 nm is shown below.

$$\phi = \frac{\ln\left(\frac{[TOC_0]}{[TOC_f]}\right)}{k_{s(254\,nm)}t} = \frac{\ln\left(\frac{5.41\times10^{-3}\ moles\ TOC/L}{1.34\times10^{-3}\ moles\ TOC/L}\right)}{\left(4.8103\times10^{-3}\frac{moles\ photons}{moles\ TOC\cdot s}\right)(180\ min)\cdot\frac{60\ s}{1\ min}} = 2.6852\times10^{-2}\frac{moles\ TOC}{E}$$

The kinetic model Equation (2.53) developed by Bolton et al. (2001), as the overall rate kinetic for TOC concentrations of less than 100 mg/L, was used to predict the effluent concentrations of TOC for the UV/H_2O_2 process.

$$-\frac{d[TOC]}{dt} = \frac{\xi p k_{TOC}}{V_T \sum_i k_{S_i}[S_i]} \tag{2.53}$$

$$-\frac{d[TOC]}{\xi p k_{TOC}} = \frac{dt}{V_T k_{H_2O_2}[H_2O_2]} \tag{4.25}$$

Equation (4.25) can be rearranged and integrated as follows:

$$-\frac{1}{\xi p k_{TOC}}\int_{TOC_0}^{TOC_f} d[TOC] = \frac{1}{V_T k_{H_2O_2}[H_2O_2]}\int_{t_0}^{t_f} dt \tag{4.26}$$

$$\ln\left(\frac{[TOC_f]}{[TOC_0]}\right) = -\left(\frac{\xi p k_{TOC} t}{V_T k_{H_2O_2}[H_2O_2]}\right) \tag{4.27}$$

$$\frac{[TOC_f]}{[TOC_0]} = e^{-\left(\frac{\xi p k_{TOC} t}{V_T k_{H_2O_2}[H_2O_2]}\right)} \tag{4.28}$$

where,

V_T = volume of the treated SSWW equal to the volume of the photoreactor (1.35 L);

p = power rating of the system (14 W); and

$\xi = G.A_b.\phi/p$ (moles/s.W), where G = total absolute photon flow (E/s) emitted from the lamp in all directions at 254 nm, A_b = fraction photons absorbed (0.12), p = power output of the lamp, and $\phi = 2.6852\times10^{-2}$ (moles/E).

Thus, Equation (4.29) was obtained from a parameter estimation method, by giving different values to $k_{TOC}/k_{H_2O_2}$ until reaching an absolute relative error of less than 10% between the model

prediction and any experimental data. The initial value for $k_{TOC}/k_{H_2O_2}$ was 7.0×10^5 1/(M.s) (Barrera, 2011) divided by 2.7×10^7 1/(M.s) (Christensen et al., 1982). When $k_{TOC}/k_{H_2O_2}$ values substituted into the model overestimated the TOC removal rate, the value was reduced, while the $k_{TOC}/k_{H_2O_2}$ values were substituted into the model underestimated the TOC removal rate, the value was increased. As a result, Equation (4.29) was used to predict the effluent concentrations of TOC from the UV/H_2O_2 process alone.

$$\frac{[TOC_f]}{[TOC_0]} = e^{-(7.9941\times10^{-6}t/[H_2O_2])} \quad (4.29)$$

The comparison between predicted values and the experimental data for the UV/H_2O_2 process alone is presented in Figure 4.44. This figure shows an agreement between the predicted model values and the experimental data. Therefore, Equation (4.29) could be used to predict the effluent TOC concentration at a specific HRT for the treatment of SSWW by UV/H_2O_2 process alone.

4.8.4. Kinetic modeling for the combined anaerobic-aerobic and UV/H_2O_2 processes

For the combined anaerobic-aerobic and UV/H_2O_2 processes, Equations (4.6), (4.11), and (4.28) were combined. As a result, Equation (4.30) was used to predict the effluent concentrations of TOC for the combined anaerobic-aerobic and UV/H_2O_2 processes.

$$S_f = \left(\frac{[(\{[S_0/(1+0.3027\mathrm{t})]/(1+0.1341\mathrm{t})\}/(1+0.0949\mathrm{t}))/(1+0.0465\mathrm{t})]/(1+0.0442\mathrm{t})}{(1+0.2201t)}\right)\cdot e^{-(0.0393t/[H_2O_2])} \quad (4.30)$$

The comparison between predicted values and the experimental data for the combined anaerobic-aerobic and UV/H_2O_2 processes is presented in Figure 4.45. This figure shows an agreement between the predicted model values and the experimental data. Therefore, Equation (4.30) could be used to predict the effluent TOC concentration at a specific HRT for the treatment of SSWW using combined anaerobic-aerobic and UV/H_2O_2 processes.

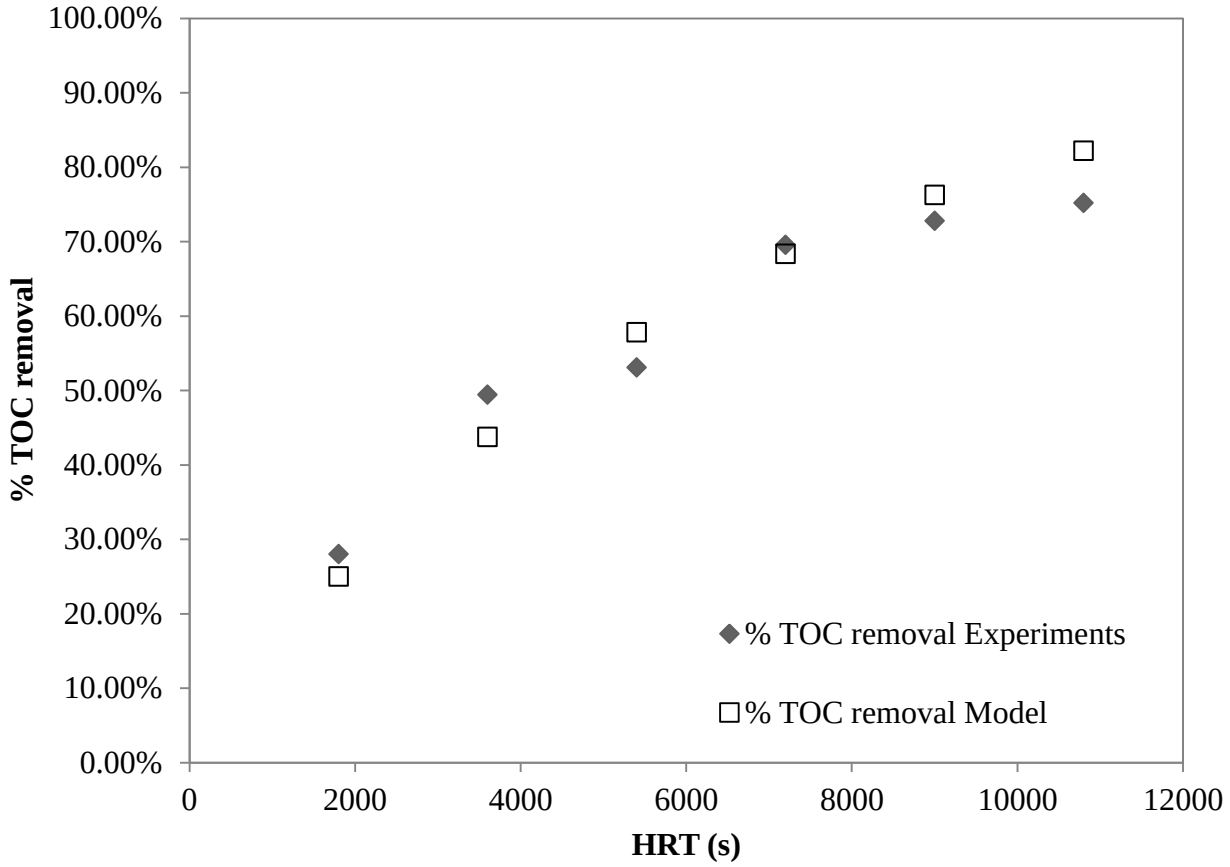


Figure 4.44. TOC removal comparison of the predicted values using Equation (4.29) and the experimental data of the SSWW treatment using UV/H_2O_2 process alone in continuous mode without recycling.

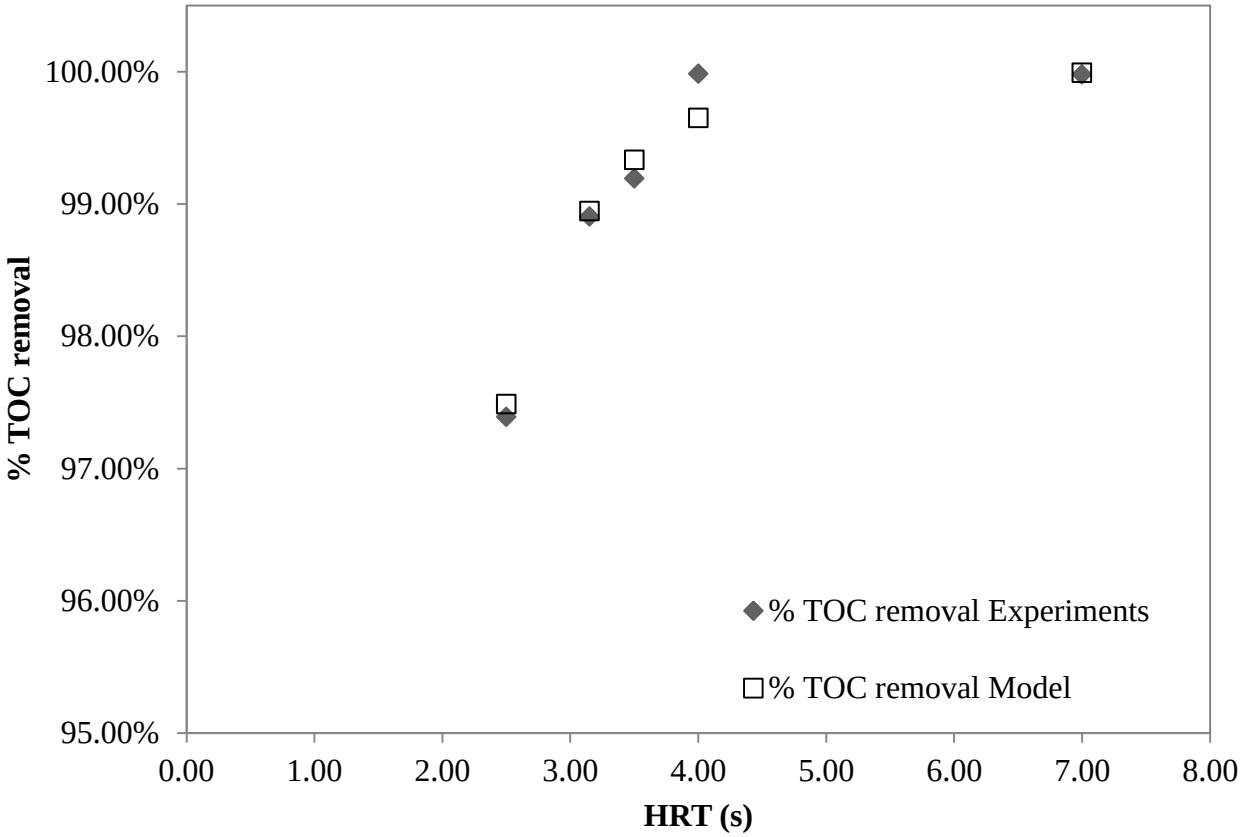


Figure 4.45. TOC removal comparison of the predicted values using Equation (4.30) and the experimental data of the SSWW treatment using combined anaerobic-aerobic and UV/H_2O_2 processes in continuous mode without recycling.

4.8.5. Optimization of the total electricity cost and HRT to determine the best alternative on SSWW treatment

Durán et al. (2012) presented an operational cost study to evaluate three different processes for the treatment of an industrial effluent. The operational costs due to the consumption of electrical energy, reagents, and catalysts were calculated from the optimal conditions of each process, and allowed to determine the most economically feasible system. This section will be based on the procedure suggested by Durán et al. (2012) in order to determine the best alternative of this study.

Table 4.6 summarizes the technical conditions and performance of different processes evaluated in this study, including UV/H_2O_2 alone; aerobic AS alone; ABR alone; combined anaerobic-aerobic processes; combined aerobic-anaerobic processes; and combined aerobic-anaerobic and UV/H_2O_2 processes. Table 4.6 also summarizes the amount of H_2O_2 consumed in each of the processes involved in the economic study.

Table 4.6. Technical conditions of the processes for the economic study

Process	Volume (L)	No. of Pumps	HRT (h)	H_2O_2 consumed (L)	%TOC removal
UV/H_2O_2	1.35	1	3	0.0940	75.22%
ABR	33.70	1	168	n/a	89.47%
Aerobic AS	12.00	1	168	n/a	94.53%
Combined Ae-Ana	45.70	2	150	n/a	96.10%
Combined Ana-Ae	45.70	2	150	n/a	96.36%
Combined Ana-Ae-UV	47.05	3	96	0.2814	99.98%

Note: Ana, anaerobic; Ae, Aerobic; UV, UV/H_2O_2

The economic analysis was carried out by analyzing the degradation of TOC in the SSWW. According to Bolton et al. (2001), the cost of electricity per mass of TOC removed can be estimated by Equation (4.31), which was defined for high TOC influent concentration because the reaction rate of TOC is directly proportional to the rate of electricity used (Bolton et al., 2001; Cao 2009). According to the Ontario Energy Board (OEB, 2011), the market price of electricity based on tiered prices is $0.071/KWh. The prices of H_2O_2 and the electrical consumptions of the different devices used for calculating the costs are shown in Table 4.7 with the assumption of a common TOC concentration in the SSWW influent of 1,000 mg/L.

$$J = E_r \left[\frac{1000Pt}{V(TOC_0 - TOC_f)}\right] \quad (4.31)$$

where,

J = electricity cost ($/kg);

E_r = energy rate ($/kWh);

P = power rating of the system (W);

t = hydraulic retention time (h);

V = volume of the reactor (L);

TOC_0 = total organic carbon concentration in the influent (mg/L); and

TOC_f = total organic carbon concentration in the influent (mg/L);

Table 4.7. Electric power and costs of electricity and H_2O_2.

Item	Electric Power (kW)
UV/H_2O_2	
Lamp	0.125
Pump	0.080
Mini-pump for H_2O_2 dosage	0.007
Power Rating	*0.212*
ABR	
Pump	0.080
Power Rating	*0.080*
Aerobic AS	
Pump	0.080
Diffuser	0.120
Power Rating	*0.200*
Combined Anaerobic-Aerobic	
Pumps	0.150
Diffuser	0.100
Power Rating	*0.250*
Combined Aerobic-Anaerobic	
Pumps	0.120
Diffuser	0.100
Power Rating	*0.220*
Combined Aerobic-Anaerobic-UV/H_2O_2	
Lamp	0.125
Pumps	0.200
Diffuser	0.120
mini-pump for H_2O_2 dosage	0.005
Power Rating	*0.450*
Energy Cost (Ontario Energy Board 2011: $0.071/KWh	
Hydrogen peroxide (H_2O_2) cost = $2.50/L	

Equation (4.31) was used to calculate the electricity costs per mass of TOC removed with the assumption of an influent concentration of 1,000 mgTOC/L. A summary of the obtained values is presented in Tables 4.8 to 4.13, including ABR process alone, aerobic AS process alone, UV/H_2O_2 process alone, combined anaerobic-aerobic processes, combined aerobic-anaerobic processes, and combined anaerobic-aerobic and UV/H_2O_2. Equations (4.6), (4.11), (4.14), (4.16), (4.28), and (4.30), were used for each process, respectively.

Table 4.8. Calculated values of the electricity cost per mass TOC removed for the ABR process alone.

					ABR Process Alone			
HRT (h)	**TOC_0 (mg/L)**	**V (L)**	**TOC_f (mg/L)**	**TOC removed (g)**	**% TOC removal**	**J ($/kg)**	**AOC* ($)**	**OCV** of SSWW ($/m^3)**
0.5	1000	33.7	990.66	3.15	0.93%	0.38	0.00	0.04
1.0	1000	33.7	981.43	6.26	1.86%	0.38	0.00	0.07
2.0	1000	33.7	963.31	12.37	3.67%	0.38	0.00	0.14
3.0	1000	33.7	945.63	18.32	5.44%	0.39	0.01	0.21
4.0	1000	33.7	928.37	24.14	7.16%	0.39	0.01	0.28
5.0	1000	33.7	911.53	29.82	8.85%	0.40	0.01	0.35
6.0	1000	33.7	895.08	35.36	10.49%	0.40	0.01	0.42
7.0	1000	33.7	879.03	40.77	12.10%	0.41	0.02	0.49
8.0	1000	33.7	863.35	46.05	13.67%	0.41	0.02	0.56
9.0	1000	33.7	848.03	51.21	15.20%	0.42	0.02	0.63
10.0	1000	33.7	833.07	56.25	16.69%	0.42	0.02	0.70
11.0	1000	33.7	818.46	61.18	18.15%	0.43	0.03	0.77
12.0	1000	33.7	804.18	65.99	19.58%	0.43	0.03	0.84
13.0	1000	33.7	790.22	70.70	20.98%	0.44	0.03	0.91
14.0	1000	33.7	776.58	75.29	22.34%	0.44	0.03	0.98
15.0	1000	33.7	763.24	79.79	23.68%	0.44	0.04	1.05
16.0	1000	33.7	750.20	84.18	24.98%	0.45	0.04	1.12
17.0	1000	33.7	737.46	88.48	26.25%	0.45	0.04	1.19
18.0	1000	33.7	724.99	92.68	27.50%	0.46	0.04	1.26
19.0	1000	33.7	712.79	96.79	28.72%	0.46	0.04	1.33
20.0	1000	33.7	700.87	100.81	29.91%	0.47	0.05	1.40
21.0	1000	33.7	689.20	104.74	31.08%	0.47	0.05	1.47
22.0	1000	33.7	677.78	108.59	32.22%	0.48	0.05	1.55
23.0	1000	33.7	666.60	112.35	33.34%	0.48	0.05	1.62
24.0	1000	33.7	655.67	116.04	34.43%	0.49	0.06	1.69
25.0	1000	33.7	644.97	119.65	35.50%	0.49	0.06	1.76
26.0	1000	33.7	634.49	123.18	36.55%	0.50	0.06	1.83
27.0	1000	33.7	624.23	126.63	37.58%	0.50	0.06	1.90
28.0	1000	33.7	614.19	130.02	38.58%	0.51	0.07	1.97
29.0	1000	33.7	604.35	133.33	39.56%	0.51	0.07	2.04
30.0	1000	33.7	594.72	136.58	40.53%	0.52	0.07	2.11
31.0	1000	33.7	585.28	139.76	41.47%	0.52	0.07	2.18
32.0	1000	33.7	576.04	142.87	42.40%	0.53	0.08	2.25
33.0	1000	33.7	566.99	145.92	43.30%	0.54	0.08	2.32
34.0	1000	33.7	558.12	148.91	44.19%	0.54	0.08	2.39
35.0	1000	33.7	549.42	151.84	45.06%	0.55	0.08	2.46
36.0	1000	33.7	540.91	154.71	45.91%	0.55	0.09	2.53
37.0	1000	33.7	532.56	157.53	46.74%	0.56	0.09	2.60
38.0	1000	33.7	524.37	160.29	47.56%	0.56	0.09	2.67

ABR Process Alone								
HRT (h)	**TOC_0 (mg/L)**	**V (L)**	**TOC_f (mg/L)**	**TOC removed (g)**	**% TOC removal**	**J ($/kg)**	**AOC* ($)**	**OCV** of SSWW ($/m^3)**
39.0	1000	33.7	516.35	162.99	48.36%	0.57	0.09	2.74
40.0	1000	33.7	508.49	165.64	49.15%	0.57	0.09	2.81
41.0	1000	33.7	500.78	168.24	49.92%	0.58	0.10	2.88
42.0	1000	33.7	493.22	170.79	50.68%	0.58	0.10	2.95
43.0	1000	33.7	485.80	173.29	51.42%	0.59	0.10	3.02
44.0	1000	33.7	478.53	175.74	52.15%	0.59	0.10	3.09
45.0	1000	33.7	471.40	178.14	52.86%	0.60	0.11	3.16
46.0	1000	33.7	464.40	180.50	53.56%	0.60	0.11	3.23
47.0	1000	33.7	457.53	182.81	54.25%	0.61	0.11	3.30
48.0	1000	33.7	450.80	185.08	54.92%	0.61	0.11	3.37
49.0	1000	33.7	444.19	187.31	55.58%	0.62	0.12	3.44
50.0	1000	33.7	437.71	189.49	56.23%	0.62	0.12	3.51
51.0	1000	33.7	431.34	191.64	56.87%	0.63	0.12	3.58
52.0	1000	33.7	425.10	193.74	57.49%	0.64	0.12	3.65
53.0	1000	33.7	418.97	195.81	58.10%	0.64	0.13	3.72
54.0	1000	33.7	412.95	197.84	58.70%	0.65	0.13	3.79
55.0	1000	33.7	407.04	199.83	59.30%	0.65	0.13	3.86
56.0	1000	33.7	401.24	201.78	59.88%	0.66	0.13	3.93
57.0	1000	33.7	395.55	203.70	60.44%	0.66	0.13	4.00
58.0	1000	33.7	389.96	205.58	61.00%	0.67	0.14	4.07
59.0	1000	33.7	384.47	207.43	61.55%	0.67	0.14	4.14
60.0	1000	33.7	379.08	209.25	62.09%	0.68	0.14	4.21
61.0	1000	33.7	373.78	211.04	62.62%	0.68	0.14	4.28
62.0	1000	33.7	368.58	212.79	63.14%	0.69	0.15	4.35
63.0	1000	33.7	363.47	214.51	63.65%	0.70	0.15	4.42
64.0	1000	33.7	358.45	216.20	64.16%	0.70	0.15	4.49
65.0	1000	33.7	353.51	217.87	64.65%	0.71	0.15	4.56
66.0	1000	33.7	348.67	219.50	65.13%	0.71	0.16	4.64
67.0	1000	33.7	343.91	221.10	65.61%	0.72	0.16	4.71
68.0	1000	33.7	339.23	222.68	66.08%	0.72	0.16	4.78
69.0	1000	33.7	334.63	224.23	66.54%	0.73	0.16	4.85
70.0	1000	33.7	330.11	225.75	66.99%	0.73	0.17	4.92
71.0	1000	33.7	325.67	227.25	67.43%	0.74	0.17	4.99
72.0	1000	33.7	321.30	228.72	67.87%	0.75	0.17	5.06

* AOC, absolute operation costs. ** OCV, Operation costs per volume.

Table 4.9. Calculated values of the electricity cost per mass TOC removed for the aerobic AS process alone.

Aerobic AS Process Alone								
HRT (h)	**TOC_0 (mg/L)**	**V (L)**	**TOC_f (mg/L)**	**TOC removed (g)**	**% TOC removal**	**J ($/kg)**	**AOC* ($)**	**OCV** of SSWW ($/m^3)**
0.5	1000	12	951.12	5.87	4.89%	0.50	0.00	0.25
1.0	1000	12	906.79	11.19	9.32%	0.53	0.01	0.49
2.0	1000	12	829.48	20.46	17.05%	0.58	0.01	0.99
3.0	1000	12	764.31	28.28	23.57%	0.63	0.02	1.48
4.0	1000	12	708.64	34.96	29.14%	0.68	0.02	1.97
5.0	1000	12	660.53	40.74	33.95%	0.73	0.03	2.47
6.0	1000	12	618.53	45.78	38.15%	0.78	0.04	2.96
7.0	1000	12	581.56	50.21	41.84%	0.82	0.04	3.45
8.0	1000	12	548.75	54.15	45.12%	0.87	0.05	3.94
9.0	1000	12	519.45	57.67	48.05%	0.92	0.05	4.44

Aerobic AS Process Alone								
HRT (h)	**TOC_0 (mg/L)**	**V (L)**	**TOC_f (mg/L)**	**TOC removed (g)**	**% TOC removal**	**J ($/kg)**	**AOC* ($)**	**OCV** of SSWW ($/m^3)**
10.0	1000	12	493.12	60.83	50.69%	0.97	0.06	4.93
11.0	1000	12	469.33	63.68	53.07%	1.02	0.07	5.42
12.0	1000	12	447.73	66.27	55.23%	1.07	0.07	5.92
13.0	1000	12	428.03	68.64	57.20%	1.12	0.08	6.41
14.0	1000	12	410.00	70.80	59.00%	1.17	0.08	6.90
15.0	1000	12	393.42	72.79	60.66%	1.22	0.09	7.40
16.0	1000	12	378.13	74.62	62.19%	1.27	0.09	7.89
17.0	1000	12	363.98	76.32	63.60%	1.32	0.10	8.38
18.0	1000	12	350.85	77.90	64.91%	1.37	0.11	8.88
19.0	1000	12	338.64	79.36	66.14%	1.42	0.11	9.37
20.0	1000	12	327.25	80.73	67.28%	1.47	0.12	9.86
21.0	1000	12	316.60	82.01	68.34%	1.52	0.12	10.35
22.0	1000	12	306.62	83.21	69.34%	1.56	0.13	10.85
23.0	1000	12	297.25	84.33	70.27%	1.61	0.14	11.34
24.0	1000	12	288.44	85.39	71.16%	1.66	0.14	11.83
25.0	1000	12	280.13	86.38	71.99%	1.71	0.15	12.33
26.0	1000	12	272.29	87.32	72.77%	1.76	0.15	12.82
27.0	1000	12	264.88	88.21	73.51%	1.81	0.16	13.31
28.0	1000	12	257.86	89.06	74.21%	1.86	0.17	13.81
29.0	1000	12	251.20	89.86	74.88%	1.91	0.17	14.30
30.0	1000	12	244.88	90.61	75.51%	1.96	0.18	14.79
31.0	1000	12	238.87	91.34	76.11%	2.01	0.18	15.28
32.0	1000	12	233.14	92.02	76.69%	2.06	0.19	15.78
33.0	1000	12	227.68	92.68	77.23%	2.11	0.20	16.27
34.0	1000	12	222.48	93.30	77.75%	2.16	0.20	16.76
35.0	1000	12	217.50	93.90	78.25%	2.21	0.21	17.26
36.0	1000	12	212.75	94.47	78.73%	2.25	0.21	17.75
37.0	1000	12	208.19	95.02	79.18%	2.30	0.22	18.24
38.0	1000	12	203.83	95.54	79.62%	2.35	0.22	18.74
39.0	1000	12	199.65	96.04	80.04%	2.40	0.23	19.23
40.0	1000	12	195.63	96.52	80.44%	2.45	0.24	19.72
41.0	1000	12	191.78	96.99	80.82%	2.50	0.24	20.22
42.0	1000	12	188.07	97.43	81.19%	2.55	0.25	20.71
43.0	1000	12	184.50	97.86	81.55%	2.60	0.25	21.20
44.0	1000	12	181.07	98.27	81.89%	2.65	0.26	21.69
45.0	1000	12	177.76	98.67	82.22%	2.70	0.27	22.19
46.0	1000	12	174.57	99.05	82.54%	2.75	0.27	22.68
47.0	1000	12	171.49	99.42	82.85%	2.80	0.28	23.17
48.0	1000	12	168.52	99.78	83.15%	2.85	0.28	23.67
49.0	1000	12	165.65	100.12	83.43%	2.90	0.29	24.16
50.0	1000	12	162.88	100.45	83.71%	2.94	0.30	24.65
51.0	1000	12	160.20	100.78	83.98%	2.99	0.30	25.15
52.0	1000	12	157.60	101.09	84.24%	3.04	0.31	25.64
53.0	1000	12	155.09	101.39	84.49%	3.09	0.31	26.13
54.0	1000	12	152.66	101.68	84.73%	3.14	0.32	26.63
55.0	1000	12	150.30	101.96	84.97%	3.19	0.33	27.12
56.0	1000	12	148.01	102.24	85.20%	3.24	0.33	27.61
57.0	1000	12	145.79	102.50	85.42%	3.29	0.34	28.10
58.0	1000	12	143.64	102.76	85.64%	3.34	0.34	28.60
59.0	1000	12	141.55	103.01	85.84%	3.39	0.35	29.09
60.0	1000	12	139.52	103.26	86.05%	3.44	0.36	29.58
61.0	1000	12	137.55	103.49	86.25%	3.49	0.36	30.08
62.0	1000	12	135.63	103.72	86.44%	3.54	0.37	30.57
63.0	1000	12	133.77	103.95	86.62%	3.59	0.37	31.06
64.0	1000	12	131.95	104.17	86.80%	3.64	0.38	31.56

Aerobic AS Process Alone								
HRT (h)	**TOC_0 (mg/L)**	**V (L)**	**TOC_f (mg/L)**	**TOC removed (g)**	**% TOC removal**	**J ($/kg)**	**AOC* ($)**	**OCV** of SSWW ($/m^3)**
65.0	1000	12	130.19	104.38	86.98%	3.68	0.38	32.05
66.0	1000	12	128.47	104.58	87.15%	3.73	0.39	32.54
67.0	1000	12	126.79	104.78	87.32%	3.78	0.40	33.03
68.0	1000	12	125.16	104.98	87.48%	3.83	0.40	33.53
69.0	1000	12	123.57	105.17	87.64%	3.88	0.41	34.02
70.0	1000	12	122.02	105.36	87.80%	3.93	0.41	34.51
71.0	1000	12	120.51	105.54	87.95%	3.98	0.42	35.01
72.0	1000	12	119.04	105.72	88.10%	4.03	0.43	35.50

* AOC, absolute operation costs. ** OCV, Operation costs per volume.

Table 4.10. Calculated values of the electricity cost per mass TOC removed for the UV/H_2O_2 process alone.

UV/H_2O_2 Process Alone								
HRT (h)	**TOC_0 (mg/L)**	**V (L)**	**TOC_f (mg/L)**	**TOC removed (g)**	**% TOC removal**	**J ($/kg)**	**AOC* ($)**	**OCV** of SSWW ($/m^3)**
0.5	1000	1.35	995.22	0.06	0.48%	48.54	0.00	2.32
1.0	1000	1.35	990.45	0.13	0.95%	48.66	0.01	4.65
2.0	1000	1.35	981.00	0.26	1.90%	48.89	0.01	9.29
3.0	1000	1.35	971.63	0.38	2.84%	49.13	0.02	13.94
4.0	1000	1.35	962.36	0.51	3.76%	49.36	0.03	18.58
5.0	1000	1.35	953.17	0.63	4.68%	49.60	0.03	23.23
6.0	1000	1.35	944.07	0.76	5.59%	49.84	0.04	27.87
7.0	1000	1.35	935.05	0.88	6.49%	50.07	0.04	32.52
8.0	1000	1.35	926.13	1.00	7.39%	50.31	0.05	37.17
9.0	1000	1.35	917.29	1.12	8.27%	50.55	0.06	41.81
10.0	1000	1.35	908.53	1.23	9.15%	50.79	0.06	46.46
11.0	1000	1.35	899.85	1.35	10.01%	51.03	0.07	51.10
12.0	1000	1.35	891.26	1.47	10.87%	51.27	0.08	55.75
13.0	1000	1.35	882.75	1.58	11.72%	51.51	0.08	60.39
14.0	1000	1.35	874.33	1.70	12.57%	51.75	0.09	65.04
15.0	1000	1.35	865.98	1.81	13.40%	52.00	0.09	69.69
16.0	1000	1.35	857.71	1.92	14.23%	52.24	0.10	74.33
17.0	1000	1.35	849.52	2.03	15.05%	52.48	0.11	78.98
18.0	1000	1.35	841.41	2.14	15.86%	52.73	0.11	83.62
19.0	1000	1.35	833.38	2.25	16.66%	52.98	0.12	88.27
20.0	1000	1.35	825.42	2.36	17.46%	53.22	0.13	92.91
21.0	1000	1.35	817.54	2.46	18.25%	53.47	0.13	97.56
22.0	1000	1.35	809.74	2.57	19.03%	53.72	0.14	102.20
23.0	1000	1.35	802.01	2.67	19.80%	53.97	0.14	106.85
24.0	1000	1.35	794.35	2.78	20.56%	54.22	0.15	111.50
25.0	1000	1.35	786.77	2.88	21.32%	54.47	0.16	116.14
26.0	1000	1.35	779.26	2.98	22.07%	54.72	0.16	120.79
27.0	1000	1.35	771.82	3.08	22.82%	54.97	0.17	125.43
28.0	1000	1.35	764.45	3.18	23.56%	55.22	0.18	130.08
29.0	1000	1.35	757.15	3.28	24.29%	55.48	0.18	134.72
30.0	1000	1.35	749.92	3.38	25.01%	55.73	0.19	139.37
31.0	1000	1.35	742.76	3.47	25.72%	55.99	0.19	144.02
32.0	1000	1.35	735.67	3.57	26.43%	56.24	0.20	148.66
33.0	1000	1.35	728.65	3.66	27.14%	56.50	0.21	153.31
34.0	1000	1.35	721.69	3.76	27.83%	56.75	0.21	157.95
35.0	1000	1.35	714.80	3.85	28.52%	57.01	0.22	162.60

					UV/H_2O_2 Process Alone			
HRT (h)	**TOC_0 (mg/L)**	**V (L)**	**TOC_f (mg/L)**	**TOC removed (g)**	**% TOC removal**	**J ($/kg)**	**AOC* ($)**	**OCV** of SSWW ($/m^3)**
36.0	1000	1.35	707.98	3.94	29.20%	57.27	0.23	167.24
37.0	1000	1.35	701.22	4.03	29.88%	57.53	0.23	171.89
38.0	1000	1.35	694.52	4.12	30.55%	57.79	0.24	176.54
39.0	1000	1.35	687.89	4.21	31.21%	58.05	0.24	181.18
40.0	1000	1.35	681.32	4.30	31.87%	58.31	0.25	185.83
41.0	1000	1.35	674.82	4.39	32.52%	58.57	0.26	190.47
42.0	1000	1.35	668.38	4.48	33.16%	58.84	0.26	195.12
43.0	1000	1.35	662.00	4.56	33.80%	59.10	0.27	199.76
44.0	1000	1.35	655.68	4.65	34.43%	59.37	0.28	204.41
45.0	1000	1.35	649.42	4.73	35.06%	59.63	0.28	209.06
46.0	1000	1.35	643.22	4.82	35.68%	59.90	0.29	213.70
47.0	1000	1.35	637.07	4.90	36.29%	60.16	0.29	218.35
48.0	1000	1.35	630.99	4.98	36.90%	60.43	0.30	222.99
49.0	1000	1.35	624.97	5.06	37.50%	60.70	0.31	227.64
50.0	1000	1.35	619.00	5.14	38.10%	60.97	0.31	232.28
51.0	1000	1.35	613.09	5.22	38.69%	61.24	0.32	236.93
52.0	1000	1.35	607.24	5.30	39.28%	61.51	0.33	241.58
53.0	1000	1.35	601.44	5.38	39.86%	61.78	0.33	246.22
54.0	1000	1.35	595.70	5.46	40.43%	62.05	0.34	250.87
55.0	1000	1.35	590.01	5.53	41.00%	62.32	0.34	255.51
56.0	1000	1.35	584.38	5.61	41.56%	62.60	0.35	260.16
57.0	1000	1.35	578.80	5.69	42.12%	62.87	0.36	264.80
58.0	1000	1.35	573.27	5.76	42.67%	63.14	0.36	269.45
59.0	1000	1.35	567.80	5.83	43.22%	63.42	0.37	274.10
60.0	1000	1.35	562.38	5.91	43.76%	63.69	0.38	278.74
61.0	1000	1.35	557.01	5.98	44.30%	63.97	0.38	283.39
62.0	1000	1.35	551.69	6.05	44.83%	64.25	0.39	288.03
63.0	1000	1.35	546.43	6.12	45.36%	64.53	0.40	292.68
64.0	1000	1.35	541.21	6.19	45.88%	64.81	0.40	297.32
65.0	1000	1.35	536.04	6.26	46.40%	65.09	0.41	301.97
66.0	1000	1.35	530.92	6.33	46.91%	65.37	0.41	306.61
67.0	1000	1.35	525.86	6.40	47.41%	65.65	0.42	311.26
68.0	1000	1.35	520.84	6.47	47.92%	65.93	0.43	315.91
69.0	1000	1.35	515.86	6.54	48.41%	66.21	0.43	320.55
70.0	1000	1.35	510.94	6.60	48.91%	66.49	0.44	325.20
71.0	1000	1.35	506.06	6.67	49.39%	66.78	0.45	329.84
72.0	1000	1.35	501.23	6.73	49.88%	67.06	0.45	334.49

* AOC, absolute operation costs. ** OCV, Operation costs per volume.

Table 4.11. Calculated values of the electricity cost per mass TOC removed for the combined anaerobic-aerobic processes.

					Combined Anaerobic-Aerobic Processes			
HRT (h)	**TOC_0 (mg/L)**	**V (L)**	**TOC_f (mg/L)**	**TOC removed (g)**	**% TOC removal**	**J ($/kg)**	**AOC* ($)**	**OCV** of SSWW ($/m^3)**
0.5	1000	45.7	980.43	8.94	1.96%	0.41	0.00	0.08
1.0	1000	45.7	961.40	17.64	3.86%	0.42	0.01	0.16
2.0	1000	45.7	924.85	34.35	7.52%	0.43	0.01	0.32
3.0	1000	45.7	890.20	50.18	10.98%	0.44	0.02	0.49
4.0	1000	45.7	857.32	65.20	14.27%	0.45	0.03	0.65
5.0	1000	45.7	826.11	79.47	17.39%	0.47	0.04	0.81
6.0	1000	45.7	796.44	93.03	20.36%	0.48	0.04	0.97

				Combined Anaerobic-Aerobic Processes				
HRT (h)	**TOC_0 (mg/L)**	**V (L)**	**TOC_f (mg/L)**	**TOC removed (g)**	**% TOC removal**	**J ($/kg)**	**AOC* ($)**	**OCV** of SSWW ($/m^3)**
7.0	1000	45.7	768.22	105.93	23.18%	0.49	0.05	1.13
8.0	1000	45.7	741.35	118.20	25.86%	0.50	0.06	1.29
9.0	1000	45.7	715.76	129.90	28.42%	0.51	0.07	1.46
10.0	1000	45.7	691.36	141.05	30.86%	0.52	0.07	1.62
11.0	1000	45.7	668.09	151.68	33.19%	0.54	0.08	1.78
12.0	1000	45.7	645.87	161.84	35.41%	0.55	0.09	1.94
13.0	1000	45.7	624.65	171.54	37.54%	0.56	0.10	2.10
14.0	1000	45.7	604.36	180.81	39.56%	0.57	0.10	2.27
15.0	1000	45.7	584.96	189.67	41.50%	0.58	0.11	2.43
16.0	1000	45.7	566.39	198.16	43.36%	0.60	0.12	2.59
17.0	1000	45.7	548.61	206.29	45.14%	0.61	0.13	2.75
18.0	1000	45.7	531.57	214.07	46.84%	0.62	0.13	2.91
19.0	1000	45.7	515.24	221.53	48.48%	0.63	0.14	3.07
20.0	1000	45.7	499.58	228.69	50.04%	0.65	0.15	3.24
21.0	1000	45.7	484.55	235.56	51.54%	0.66	0.16	3.40
22.0	1000	45.7	470.12	242.15	52.99%	0.67	0.16	3.56
23.0	1000	45.7	456.27	248.49	54.37%	0.68	0.17	3.72
24.0	1000	45.7	442.95	254.57	55.71%	0.70	0.18	3.88
25.0	1000	45.7	430.15	260.42	56.99%	0.71	0.18	4.05
26.0	1000	45.7	417.83	266.05	58.22%	0.72	0.19	4.21
27.0	1000	45.7	405.99	271.46	59.40%	0.74	0.20	4.37
28.0	1000	45.7	394.58	276.68	60.54%	0.75	0.21	4.53
29.0	1000	45.7	383.60	281.69	61.64%	0.76	0.21	4.69
30.0	1000	45.7	373.02	286.53	62.70%	0.77	0.22	4.86
31.0	1000	45.7	362.82	291.19	63.72%	0.79	0.23	5.02
32.0	1000	45.7	352.99	295.68	64.70%	0.80	0.24	5.18
33.0	1000	45.7	343.51	300.01	65.65%	0.81	0.24	5.34
34.0	1000	45.7	334.37	304.19	66.56%	0.83	0.25	5.50
35.0	1000	45.7	325.54	308.23	67.45%	0.84	0.26	5.66
36.0	1000	45.7	317.02	312.12	68.30%	0.85	0.27	5.83
37.0	1000	45.7	308.78	315.89	69.12%	0.87	0.27	5.99
38.0	1000	45.7	300.83	319.52	69.92%	0.88	0.28	6.15
39.0	1000	45.7	293.15	323.03	70.69%	0.89	0.29	6.31
40.0	1000	45.7	285.72	326.43	71.43%	0.91	0.30	6.47
41.0	1000	45.7	278.53	329.71	72.15%	0.92	0.30	6.64
42.0	1000	45.7	271.59	332.89	72.84%	0.93	0.31	6.80
43.0	1000	45.7	264.86	335.96	73.51%	0.95	0.32	6.96
44.0	1000	45.7	258.36	338.93	74.16%	0.96	0.33	7.12
45.0	1000	45.7	252.06	341.81	74.79%	0.97	0.33	7.28
46.0	1000	45.7	245.96	344.60	75.40%	0.99	0.34	7.44
47.0	1000	45.7	240.05	347.30	76.00%	1.00	0.35	7.61
48.0	1000	45.7	234.32	349.91	76.57%	1.01	0.36	7.77
49.0	1000	45.7	228.77	352.45	77.12%	1.03	0.36	7.93
50.0	1000	45.7	223.40	354.91	77.66%	1.04	0.37	8.09
51.0	1000	45.7	218.18	357.29	78.18%	1.06	0.38	8.25
52.0	1000	45.7	213.12	359.60	78.69%	1.07	0.38	8.42
53.0	1000	45.7	208.22	361.84	79.18%	1.08	0.39	8.58
54.0	1000	45.7	203.46	364.02	79.65%	1.10	0.40	8.74
55.0	1000	45.7	198.84	366.13	80.12%	1.11	0.41	8.90
56.0	1000	45.7	194.35	368.18	80.56%	1.12	0.41	9.06
57.0	1000	45.7	190.00	370.17	81.00%	1.14	0.42	9.22
58.0	1000	45.7	185.77	372.10	81.42%	1.15	0.43	9.39
59.0	1000	45.7	181.66	373.98	81.83%	1.17	0.44	9.55
60.0	1000	45.7	177.67	375.81	82.23%	1.18	0.44	9.71
61.0	1000	45.7	173.79	377.58	82.62%	1.19	0.45	9.87

Combined Anaerobic-Aerobic Processes								
HRT (h)	**TOC_0 (mg/L)**	**V (L)**	**TOC_f (mg/L)**	**TOC removed (g)**	**% TOC removal**	**J ($/kg)**	**AOC* ($)**	**OCV** of SSWW ($/m^3)**
62.0	1000	45.7	170.02	379.30	83.00%	1.21	0.46	10.03
63.0	1000	45.7	166.35	380.98	83.36%	1.22	0.47	10.20
64.0	1000	45.7	162.79	382.60	83.72%	1.24	0.47	10.36
65.0	1000	45.7	159.33	384.19	84.07%	1.25	0.48	10.52
66.0	1000	45.7	155.95	385.73	84.40%	1.27	0.49	10.68
67.0	1000	45.7	152.67	387.23	84.73%	1.28	0.50	10.84
68.0	1000	45.7	149.48	388.69	85.05%	1.29	0.50	11.00
69.0	1000	45.7	146.37	390.11	85.36%	1.31	0.51	11.17
70.0	1000	45.7	143.35	391.49	85.66%	1.32	0.52	11.33
71.0	1000	45.7	140.41	392.83	85.96%	1.34	0.53	11.49
72.0	1000	45.7	137.54	394.14	86.25%	1.35	0.53	11.65

* AOC, absolute operation costs. ** OCV, Operation costs per volume.

Table 4.12. Calculated values of the electricity cost per mass TOC removed for the combined aerobic-anaerobic processes.

Combined Aerobic-Anaerobic Processes								
HRT (h)	**TOC_0 (mg/L)**	**V (L)**	**TOC_f (mg/L)**	**TOC removed (g)**	**% TOC removal**	**J ($/kg)**	**AOC* ($)**	**OCV** of SSWW ($/m^3)**
0.5	1000	45.7	977.72	10.18	2.23%	0.36	0.00	0.08
1.0	1000	45.7	956.20	20.01	4.38%	0.37	0.01	0.16
2.0	1000	45.7	915.31	38.70	8.47%	0.38	0.01	0.32
3.0	1000	45.7	877.06	56.18	12.29%	0.39	0.02	0.49
4.0	1000	45.7	841.21	72.57	15.88%	0.41	0.03	0.65
5.0	1000	45.7	807.55	87.95	19.24%	0.42	0.04	0.81
6.0	1000	45.7	775.90	102.41	22.41%	0.43	0.04	0.97
7.0	1000	45.7	746.10	116.03	25.39%	0.45	0.05	1.13
8.0	1000	45.7	717.99	128.88	28.20%	0.46	0.06	1.29
9.0	1000	45.7	691.44	141.01	30.86%	0.47	0.07	1.46
10.0	1000	45.7	666.34	152.48	33.37%	0.49	0.07	1.62
11.0	1000	45.7	642.58	163.34	35.74%	0.50	0.08	1.78
12.0	1000	45.7	620.06	173.63	37.99%	0.51	0.09	1.94
13.0	1000	45.7	598.68	183.40	40.13%	0.52	0.10	2.10
14.0	1000	45.7	578.38	192.68	42.16%	0.54	0.10	2.27
15.0	1000	45.7	559.08	201.50	44.09%	0.55	0.11	2.43
16.0	1000	45.7	540.70	209.90	45.93%	0.56	0.12	2.59
17.0	1000	45.7	523.20	217.90	47.68%	0.58	0.13	2.75
18.0	1000	45.7	506.51	225.52	49.35%	0.59	0.13	2.91
19.0	1000	45.7	490.59	232.80	50.94%	0.60	0.14	3.07
20.0	1000	45.7	475.38	239.75	52.46%	0.62	0.15	3.24
21.0	1000	45.7	460.84	246.40	53.92%	0.63	0.16	3.40
22.0	1000	45.7	446.94	252.75	55.31%	0.64	0.16	3.56
23.0	1000	45.7	433.63	258.83	56.64%	0.66	0.17	3.72
24.0	1000	45.7	420.88	264.66	57.91%	0.67	0.18	3.88
25.0	1000	45.7	408.66	270.24	59.13%	0.68	0.18	4.05
26.0	1000	45.7	396.94	275.60	60.31%	0.70	0.19	4.21
27.0	1000	45.7	385.70	280.74	61.43%	0.71	0.20	4.37
28.0	1000	45.7	374.90	285.67	62.51%	0.72	0.21	4.53
29.0	1000	45.7	364.52	290.41	63.55%	0.74	0.21	4.69
30.0	1000	45.7	354.55	294.97	64.55%	0.75	0.22	4.86
31.0	1000	45.7	344.95	299.36	65.50%	0.77	0.23	5.02
32.0	1000	45.7	335.72	303.58	66.43%	0.78	0.24	5.18

Combined Aerobic-Anaerobic Processes								
HRT (h)	**TOC_0 (mg/L)**	**V (L)**	**TOC_f (mg/L)**	**TOC removed (g)**	**% TOC removal**	**J ($/kg)**	**AOC* ($)**	**OCV** of SSWW ($/m^3)**
33.0	1000	45.7	326.83	307.64	67.32%	0.79	0.24	5.34
34.0	1000	45.7	318.26	311.55	68.17%	0.81	0.25	5.50
35.0	1000	45.7	310.01	315.32	69.00%	0.82	0.26	5.66
36.0	1000	45.7	302.05	318.96	69.79%	0.83	0.27	5.83
37.0	1000	45.7	294.38	322.47	70.56%	0.85	0.27	5.99
38.0	1000	45.7	286.97	325.85	71.30%	0.86	0.28	6.15
39.0	1000	45.7	279.82	329.12	72.02%	0.88	0.29	6.31
40.0	1000	45.7	272.91	332.28	72.71%	0.89	0.30	6.47
41.0	1000	45.7	266.24	335.33	73.38%	0.90	0.30	6.64
42.0	1000	45.7	259.79	338.28	74.02%	0.92	0.31	6.80
43.0	1000	45.7	253.55	341.13	74.65%	0.93	0.32	6.96
44.0	1000	45.7	247.52	343.89	75.25%	0.95	0.33	7.12
45.0	1000	45.7	241.68	346.55	75.83%	0.96	0.33	7.28
46.0	1000	45.7	236.03	349.14	76.40%	0.97	0.34	7.44
47.0	1000	45.7	230.55	351.64	76.94%	0.99	0.35	7.61
48.0	1000	45.7	225.25	354.06	77.47%	1.00	0.36	7.77
49.0	1000	45.7	220.12	356.41	77.99%	1.02	0.36	7.93
50.0	1000	45.7	215.14	358.68	78.49%	1.03	0.37	8.09
51.0	1000	45.7	210.32	360.89	78.97%	1.05	0.38	8.25
52.0	1000	45.7	205.64	363.02	79.44%	1.06	0.38	8.42
53.0	1000	45.7	201.10	365.10	79.89%	1.07	0.39	8.58
54.0	1000	45.7	196.69	367.11	80.33%	1.09	0.40	8.74
55.0	1000	45.7	192.42	369.07	80.76%	1.10	0.41	8.90
56.0	1000	45.7	188.27	370.96	81.17%	1.12	0.41	9.06
57.0	1000	45.7	184.24	372.80	81.58%	1.13	0.42	9.22
58.0	1000	45.7	180.32	374.59	81.97%	1.15	0.43	9.39
59.0	1000	45.7	176.52	376.33	82.35%	1.16	0.44	9.55
60.0	1000	45.7	172.82	378.02	82.72%	1.17	0.44	9.71
61.0	1000	45.7	169.22	379.66	83.08%	1.19	0.45	9.87
62.0	1000	45.7	165.73	381.26	83.43%	1.20	0.46	10.03
63.0	1000	45.7	162.33	382.82	83.77%	1.22	0.47	10.20
64.0	1000	45.7	159.02	384.33	84.10%	1.23	0.47	10.36
65.0	1000	45.7	155.81	385.80	84.42%	1.25	0.48	10.52
66.0	1000	45.7	152.68	387.23	84.73%	1.26	0.49	10.68
67.0	1000	45.7	149.63	388.62	85.04%	1.28	0.50	10.84
68.0	1000	45.7	146.66	389.98	85.33%	1.29	0.50	11.00
69.0	1000	45.7	143.77	391.30	85.62%	1.30	0.51	11.17
70.0	1000	45.7	140.96	392.58	85.90%	1.32	0.52	11.33
71.0	1000	45.7	138.22	393.84	86.18%	1.33	0.53	11.49
72.0	1000	45.7	135.55	395.06	86.45%	1.35	0.53	11.65

* AOC, absolute operation costs. ** OCV, Operation costs per volume.

Table 4.13. Calculated values of the electricity cost per mass TOC removed for the combined anaerobic-aerobic and UV/H_2O_2 processes.

Combined Anaerobic-Aerobic and UV/H_2O_2 Processes								
HRT (h)	**TOC_0 (mg/L)**	**V (L)**	**TOC_f (mg/L)**	**TOC removed (g)**	**% TOC removal**	**J ($/kg)**	**AOC* ($)**	**OCV** of SSWW ($/m^3)**
0.5	1000	47.05	966.6793	15.68	3.33%	0.42	0.01	0.14
1.0	1000	47.05	934.5376	30.80	6.55%	0.43	0.01	0.28
2.0	1000	47.05	873.6150	59.46	12.64%	0.45	0.03	0.57
3.0	1000	47.05	816.8971	86.15	18.31%	0.46	0.04	0.85

Combined Anaerobic-Aerobic and UV/H_2O_2 Processes								
HRT (h)	**TOC_0 (mg/L)**	**V (L)**	**TOC_f (mg/L)**	**TOC removed (g)**	**% TOC removal**	**J ($/kg)**	**AOC* ($)**	**OCV** of SSWW ($/$m^3$)**
4.0	1000	47.05	764.0753	111.00	23.59%	0.48	0.05	1.13
5.0	1000	47.05	714.8653	134.16	28.51%	0.50	0.07	1.41
6.0	1000	47.05	669.0048	155.73	33.10%	0.51	0.08	1.70
7.0	1000	47.05	626.2518	175.85	37.37%	0.53	0.09	1.98
8.0	1000	47.05	586.3829	194.61	41.36%	0.55	0.11	2.26
9.0	1000	47.05	549.1920	212.11	45.08%	0.56	0.12	2.55
10.0	1000	47.05	514.4884	228.43	48.55%	0.58	0.13	2.83
11.0	1000	47.05	482.0960	243.67	51.79%	0.60	0.15	3.11
12.0	1000	47.05	451.8520	257.90	54.81%	0.62	0.16	3.40
13.0	1000	47.05	423.6056	271.19	57.64%	0.64	0.17	3.68
14.0	1000	47.05	397.2173	283.61	60.28%	0.66	0.19	3.96
15.0	1000	47.05	372.5581	295.21	62.74%	0.68	0.20	4.24
16.0	1000	47.05	349.5082	306.06	65.05%	0.70	0.21	4.53
17.0	1000	47.05	327.9569	316.20	67.20%	0.72	0.23	4.81
18.0	1000	47.05	307.8014	325.68	69.22%	0.74	0.24	5.09
19.0	1000	47.05	288.9463	334.55	71.11%	0.76	0.25	5.38
20.0	1000	47.05	271.3033	342.85	72.87%	0.78	0.27	5.66
21.0	1000	47.05	254.7903	350.62	74.52%	0.80	0.28	5.94
22.0	1000	47.05	239.3310	357.89	76.07%	0.82	0.29	6.22
23.0	1000	47.05	224.8547	364.71	77.51%	0.84	0.31	6.51
24.0	1000	47.05	211.2958	371.09	78.87%	0.86	0.32	6.79
25.0	1000	47.05	198.5929	377.06	80.14%	0.88	0.33	7.07
26.0	1000	47.05	186.6895	382.66	81.33%	0.90	0.35	7.36
27.0	1000	47.05	175.5325	387.91	82.45%	0.93	0.36	7.64
28.0	1000	47.05	165.0729	392.83	83.49%	0.95	0.37	7.92
29.0	1000	47.05	155.2650	397.45	84.47%	0.97	0.39	8.21
30.0	1000	47.05	146.0660	401.78	85.39%	0.99	0.40	8.49
31.0	1000	47.05	137.4364	405.84	86.26%	1.02	0.41	8.77
32.0	1000	47.05	129.3393	409.65	87.07%	1.04	0.43	9.05
33.0	1000	47.05	121.7401	413.22	87.83%	1.06	0.44	9.34
34.0	1000	47.05	114.6069	416.58	88.54%	1.09	0.45	9.62
35.0	1000	47.05	107.9097	419.73	89.21%	1.11	0.47	9.90
36.0	1000	47.05	101.6206	422.69	89.84%	1.13	0.48	10.19
37.0	1000	47.05	95.7136	425.47	90.43%	1.16	0.49	10.47
38.0	1000	47.05	90.1645	428.08	90.98%	1.18	0.51	10.75
39.0	1000	47.05	84.9505	430.53	91.50%	1.21	0.52	11.03
40.0	1000	47.05	80.0505	432.84	91.99%	1.23	0.53	11.32
41.0	1000	47.05	75.4448	435.00	92.46%	1.25	0.55	11.60
42.0	1000	47.05	71.1148	437.04	92.89%	1.28	0.56	11.88
43.0	1000	47.05	67.0434	438.96	93.30%	1.30	0.57	12.17
44.0	1000	47.05	63.2145	440.76	93.68%	1.33	0.59	12.45
45.0	1000	47.05	59.6129	442.45	94.04%	1.35	0.60	12.73
46.0	1000	47.05	56.2247	444.05	94.38%	1.38	0.61	13.02
47.0	1000	47.05	53.0365	445.55	94.70%	1.40	0.63	13.30
48.0	1000	47.05	50.0362	446.96	95.00%	1.43	0.64	13.58
49.0	1000	47.05	47.2122	448.29	95.28%	1.46	0.65	13.86
50.0	1000	47.05	44.5536	449.54	95.54%	1.48	0.67	14.15
51.0	1000	47.05	42.0505	450.72	95.79%	1.51	0.68	14.43
52.0	1000	47.05	39.6933	451.82	96.03%	1.53	0.69	14.71
53.0	1000	47.05	37.4731	452.87	96.25%	1.56	0.71	15.00
54.0	1000	47.05	35.3818	453.85	96.46%	1.58	0.72	15.28
55.0	1000	47.05	33.4115	454.78	96.66%	1.61	0.73	15.56
56.0	1000	47.05	31.5549	455.65	96.84%	1.64	0.75	15.84
57.0	1000	47.05	29.8052	456.48	97.02%	1.66	0.76	16.13
58.0	1000	47.05	28.1561	457.25	97.18%	1.69	0.77	16.41

Combined Anaerobic-Aerobic and UV/H_2O_2 Processes								
HRT (h)	**TOC_0 (mg/L)**	**V (L)**	**TOC_f (mg/L)**	**TOC removed (g)**	**% TOC removal**	**J ($/kg)**	**AOC* ($)**	**OCV** of SSWW ($/m^3)**
59.0	1000	47.05	26.6014	457.98	97.34%	1.71	0.79	16.69
60.0	1000	47.05	25.1357	458.67	97.49%	1.74	0.80	16.98
61.0	1000	47.05	23.7535	459.32	97.62%	1.77	0.81	17.26
62.0	1000	47.05	22.4501	459.94	97.75%	1.79	0.83	17.54
63.0	1000	47.05	21.2206	460.52	97.88%	1.82	0.84	17.83
64.0	1000	47.05	20.0608	461.06	97.99%	1.85	0.85	18.11
65.0	1000	47.05	18.9666	461.58	98.10%	1.87	0.87	18.39
66.0	1000	47.05	17.9341	462.06	98.21%	1.90	0.88	18.67
67.0	1000	47.05	16.9597	462.52	98.30%	1.93	0.89	18.96
68.0	1000	47.05	16.0400	462.95	98.40%	1.96	0.91	19.24
69.0	1000	47.05	15.1719	463.36	98.48%	1.98	0.92	19.52
70.0	1000	47.05	14.3523	463.75	98.56%	2.01	0.93	19.81
71.0	1000	47.05	13.5784	464.11	98.64%	2.04	0.95	20.09
72.0	1000	47.05	12.8476	464.46	98.72%	2.06	0.96	20.37

* AOC, absolute operation costs. ** OCV, Operation costs per volume.

Figure 4.46 shows the comparison of six techniques in terms of mineralization, measured in grams of TOC removed as a function of operation time. It can be observed that the combined anaerobic-aerobic and UV/H_2O_2 processes were more technically efficient than the other processes because they could remove 15% more TOC during the same operation time. However, this apparent advantage must be confirmed in economic terms.

Figure 4.47 shows the operational costs per kilogram of TOC removed, including optimization of HRT and H_2O_2 consumption for the six processes as a function of the percentage of TOC removed. UV/H_2O_2 alone is the less efficient technology with an optimum removal of 49.88% at a high cost of $67.06/kg of TOC removed. The TOC removal does not significantly increase by augmenting the HRT (Figure 4.47b). In contrast, it was observed that the aerobic AS is an efficient process with an optimum TOC removal of 88.10% at a cost of $4.03/kg of TOC removed (Figure 4.47a).

Figure 4.48 shows the absolute operational costs ($) compared with the percentage of TOC removed. Two important facts should be noted, the costs increase with the amount of TOC removed for the 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 4.49 summarizes the operational costs of the six processes in terms of dollars per cubic meter of treated wastewater, which is a useful measurement from an industrial viewpoint. It

is confirmed that costs ($/$m^3$) increase dramatically with TOC removal because of the electricity consumption in the UV/H_2O_2 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; only when the TOC removal is higher than 60% do the electricity costs gradually increase.

To conclude, it was determined that the optimum system is the combined anaerobic-aerobic and UV/H_2O_2 processes, 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 $11.60/$m^3$ of treated SSWW. 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 $21.65/$m^3$ of treated SSWW.

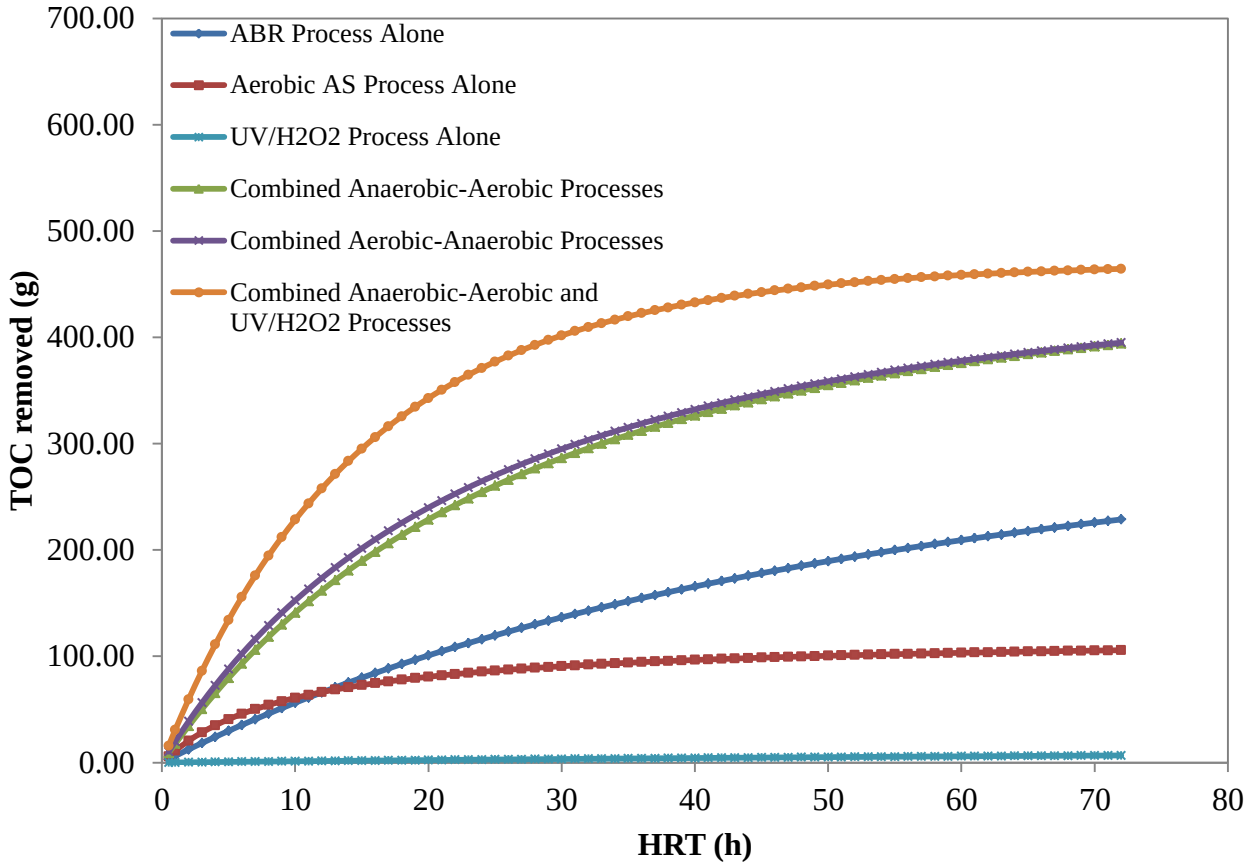


Figure 4.46. Mineralization under different processes, ABR process alone, aerobic AS process alone, UV/H_2O_2 process alone, combined anaerobic-aerobic processes, combined aerobic-anaerobic processes, and combined anaerobic-aerobic and UV/H_2O_2 processes.

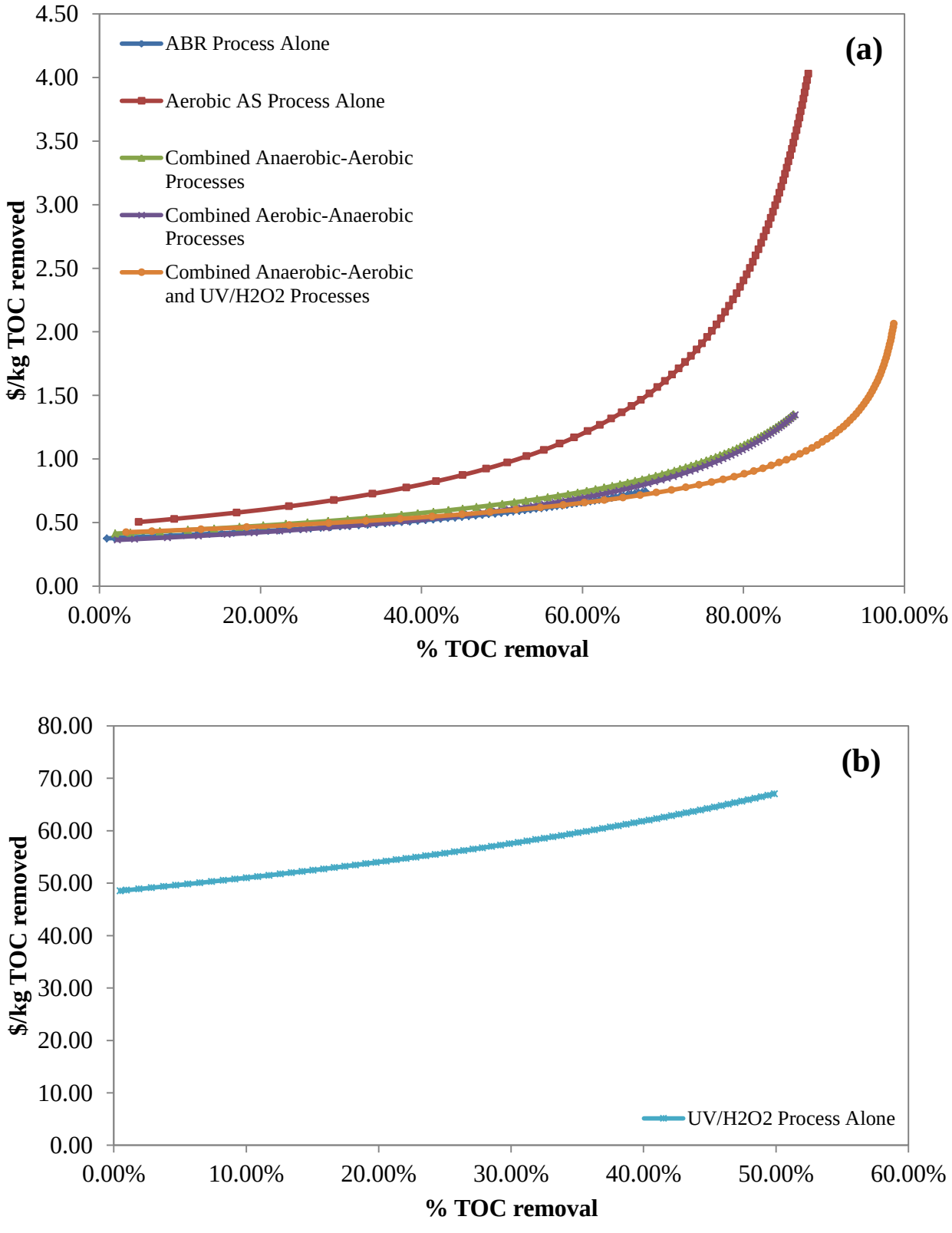


Figure 4.47. Operation costs per kilogram of TOC removed for each process as a function of TOC removal. (a) ABR process alone, aerobic AS process alone, combined anaerobic-aerobic processes, combined aerobic-anaerobic processes, and combined anaerobic-aerobic and UV/H_2O_2 processes; (b) UV/H_2O_2 process alone.

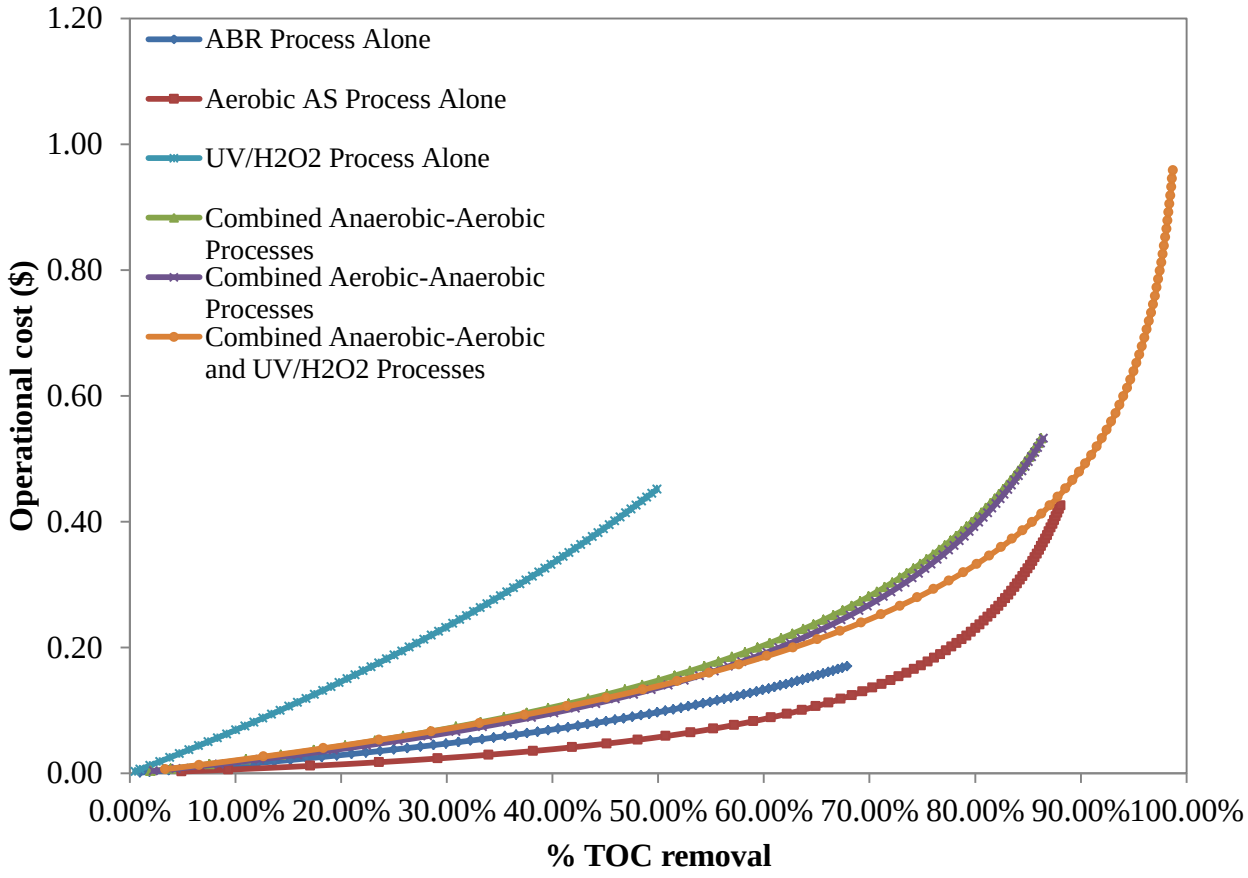


Figure 4.48. Absolute operation costs compared with TOC removed for each process, ABR process alone, aerobic AS process alone, UV/H_2O_2 process alone, combined anaerobic-aerobic processes, combined aerobic-anaerobic processes, and combined anaerobic-aerobic and UV/H_2O_2 processes.

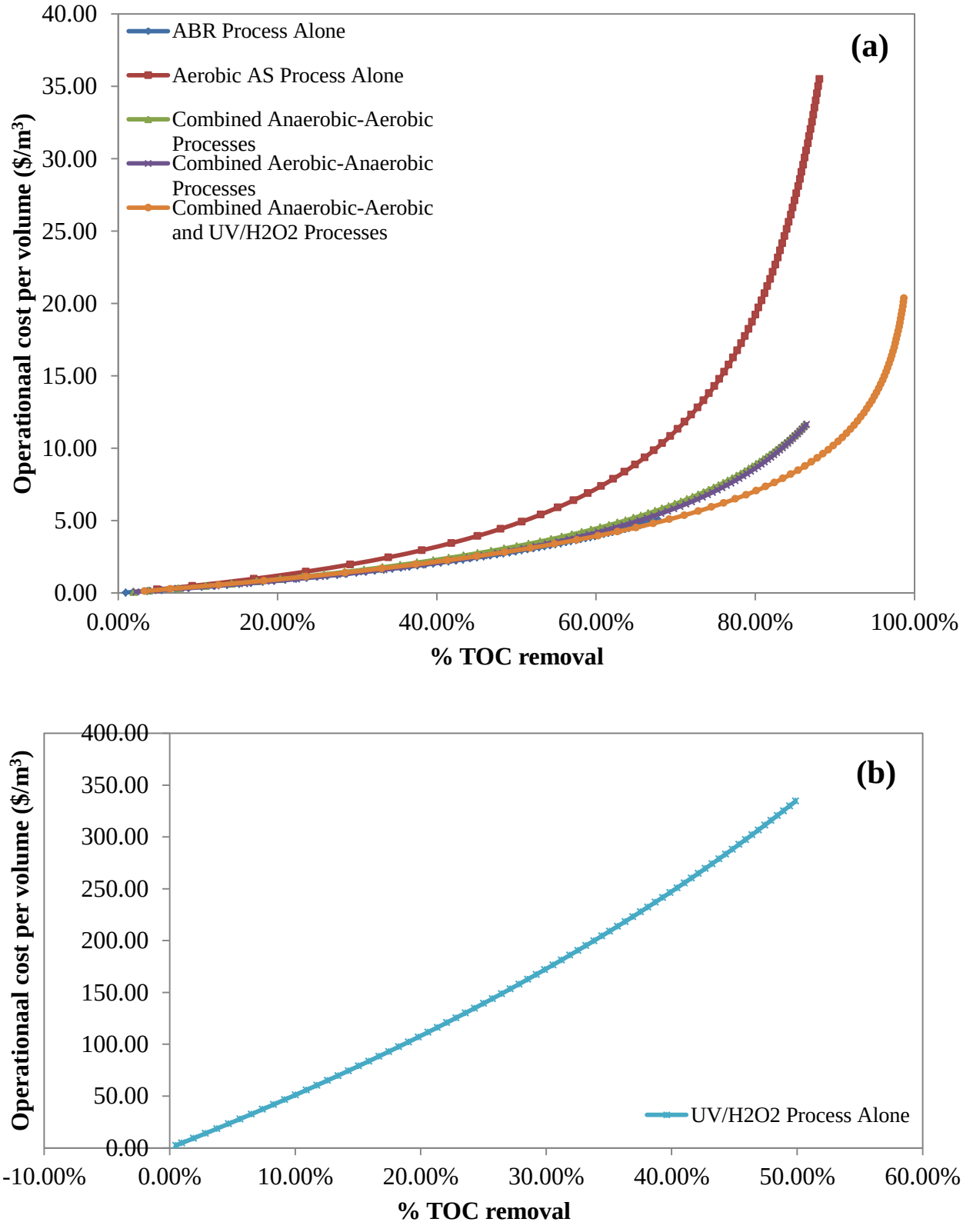


Figure 4.49. Operational costs per m^3 of treated water compared with mineralization degree: comparison between the (a) ABR process alone, aerobic AS process alone, combined anaerobic-aerobic processes, combined aerobic-anaerobic processes, combined anaerobic-aerobic and UV/H_2O_2 processes, and (b) UV/H_2O_2 process alone.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusions

The following conclusions are drawn from this thesis:

- Six different systems for the treatment of SSWW were evaluated in this study, including UV/H_2O_2 alone; aerobic AS alone; ABR alone; combined anaerobic-aerobic processes; combined aerobic-anaerobic processes; and combined anaerobic-aerobic and UV/H_2O_2. Performance of those systems was analyzed through the measurements of the removal efficiencies of TOC, TN, and $CBOD_5$.

- The ABR process demonstrated good efficiency in treating SSWW with an influent concentration of 1,008.85 mgTOC/L and 254.23 mgTN/L, a HRT of 7 days, and flow rate of 3.34 mL/min, reaching removals of TOC, TN and $CBOD_5$ of 89.47, 49.68 and 95.16%, respectively. It was also observed that at a longer HRT, the removal efficiency was higher. Although anaerobic treatment is efficient, complete stabilization of the organic matter was not possible by anaerobic treatment alone as the effluent produced by anaerobic treatment contained solubilised organic matter, which is more suited for treatment using aerobic processes or anaerobic–aerobic systems. For that reason, later post-treatment using aerobic treatment was necessary to enhance the efficiency and the biological removal of TN.

- The aerobic AS process demonstrated better efficiency than that obtained with the ABR, reaching removals of TOC, TN and $CBOD_5$ of 94.53, 73.46 and 92.19%, respectively. In spite of the results of previous studies (Cao, 2009; Cao and Mehrvar, 2011), a good removal of TN (73.46%) was achieved, varying the flow rate and influent concentration of the SSWW. This may be attributed to the well-maintained conditions in the systems, where DO concentrations were in the ranges of 0.2–1.2 mg/L and 0.4–3.2 mg/L for the ABR and the aerobic AS, respectively. Therefore, DO

concentrations above 1.0 mg/L permitted nitrification, whereas DO concentrations below 0.5 mg/L permitted denitrification.

- Although both individual anaerobic and aerobic processes demonstrated a significant efficiency to treat the SSWW, better results were found by combining anaerobic and aerobic processes, with TOC removal of 96.36%, TN removal of 80.53% and $CBOD_5$ removal of 99.38% from an influent concentration of 1,008.85 mgTOC/L and 419.77 mgTN/L at the HRT of 6.24 days and a flow rate of 3.75mL/min, using combined ABR first and then aerobic AS. The combined aerobic-anaerobic system was also studied, resulting in high efficiency for TOC, TN, and $CBOD_5$ removal rates, up to 96.10% TOC, 76.44% TN, and 99.53% $CBOD_5$ were removed. Both combined biological processes achieved good results for treating SSWW, with TOC, TN and $CBOD_5$ removal rates of above 95, 75, and 99%, respectively. Nevertheless, it was determined that combined anaerobic-aerobic processes have a considerable advantage compared to combined aerobic-anaerobic processes when treating TN, with a difference of approximately 4.09% TN removal rate. Therefore, combined anaerobic-aerobic processes were used for next experiments. Therefore, an adequate combination of anaerobic and aerobic processes is essential for the successful removal of nutrients from SSWW.

- An experiment was conducted in the recycling mode, in which the SSWW treated in the aerobic AS reactor was recycled into the ABR. It was found that recycling the flow did not significantly decrease either TOC or TN concentrations. Only a minimum variation of 0.02 and 0.05% was observed for TOC and TN removal rates, whereas the HRT of the recycling mode system doubled that of the combined anaerobic-aerobic processes; thus, making the combined system with recycling less efficient than without recirculating the flow.

- The UV/H_2O_2 process was demonstrated to be an effective technology for SSWW post-treatment. The results revealed a reasonable efficiency to treat a secondary effluent of SSWW. Up to 75.22% TOC removal rate was obtained for an influent concentration of 64.88 mgTOC/L at the HRT of 180 min with H_2O_2 concentration of 900 mg/L. Nevertheless, there were no significant changes to the TN removal rate using UV/H_2O_2 process alone. An optimum molar ratio dosage of 13.87 $mgH_2O_2/mgTOC_{in}$ was also found for the UV/H_2O_2 process. Therefore, a good alternative is to combine biological treatment and AOPs.

- The combined anaerobic-aerobic and UV/H_2O_2 processes proved to be able to enhance the treatment ability of the TOC, TN and $CBOD_5$ obtained by the other systems. Up to 99.98% TOC, 82.84% TN, and 99.69% $CBOD_5$ removals were obtained for an influent concentration of 1,004.88 mgTOC/L and 200.03 mgTN/L at the HRT of 4.00 days and a flow rate of 5.90 mL/min. These results confirm that an adequate combination of anaerobic and aerobic processes is essential for nitrogen reduction, in order to obtain removals of more than 70% (82.84% of TN removed), and they confirm that using AOPs as post-treatment guarantees the complete mineralization of the organic matter and disinfection of SSWW.

- A cost-effectiveness analysis (CEA) was used to determine the best alternative for SSWW treatment. HRT was optimized, since HRT affects the final removal efficiency of organic pollutants in wastewater and the operating and maintenance (O&M) costs of the system. The combined anaerobic-aerobic and UV/H_2O_2 processes were more technically efficient than the other processes, removing 15% more TOC during the same amount of operation time. UV/H_2O_2 alone is the less 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 processes and individual processes are comparable in economic terms. In the combined processes, the main costs are initially for pumps, reagents and air injection; only when the TOC removal is higher than 60% do the electricity costs gradually increase. Finally, it was determined that the optimum system was the combined anaerobic-aerobic and UV/H_2O_2 processes, 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 $11.60/$m^3$ of treated SSWW. It should be note 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 $21.65/$m^3$ of treated SSWW. Therefore, this confirms that the best alternative to treat SSWW is by an adequate combination of biological treatment and AOPs.

5.2. Recommendations

The following recommendations are suggested for further research on combined biological and AOPs processes:

- It is suggested to collect the biogas produced in the compartments of the ABR in order to evaluate the performances of acidogenesis and methanogenesis and a possible usage of this biogas as an energy source for the system. Following studies should take into account the accumulation of volatile fatty acids.

- Further study should be focused on the characterization of the microorganisms present in the activated sludge to determine their nitrifying and denitrifying ability.

- Further work should conduct the analysis of different intermediates that may be formed during the UV/H_2O_2 treatment.

- Further research is suggested by using different H_2O_2 dosages in the combined anaerobic-aerobic UV/H_2O_2 processes and other processes such as photo-Fenton to evaluate a possible optimization in terms of HRT.

- Further studies should use actual raw slaughterhouse wastewater in order to evaluate the applicability of the systems examined in these studies to actual conditions, and determine a possible scale up of laboratory scale systems to be adapted as onsite treatment for slaughterhouses in Ontario.

- Further research should also consider 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, which are being discharged without proper treatment, particularly in the livestock farming.

- Further work may also consider additional investigation of kinetic modeling, optimization of processes, and modeling of the combined anaerobic-aerobic and UV/H_2O_2 processes.

APPENDICES

Appendix A. Determination of theoretical TOC and TN of the SSWW

As described in Section 3.2.1, the SSWW contains 1,950 mg/L of commercial meat extract powder (Oxoid Lab Lemco L0029, Oxoid Ltd.), 200 mg/L of glycerol ($C_3H_8O_3$), 360 mg/L of ammonium chloride (NH_4Cl), 50 mg/L sodium chloride (NaCl), 30 mg/L of potassium dihydrogen orthophosphate (KH_2PO_4), 24 mg/L of calcium chloride ($CaCl_2$), and 7.5 mg/L of magnesium sulphate heptahydrate ($MgSO_4 \cdot 7H_2O$). The carbon source of the SSWW comes from the 17 amino acids present in the meat extract, described in Table A.1, and glycerol ($C_3H_8O_3$), while the nitrogen source comes from the same amino acids (Table A.1) and ammonium chloride (NH_4Cl).

An example of the calculation can be described as follows, by taking Valine ($C_5H_{11}NO_2$) to obtain the % w of TOC/w of meat extract and the % w of TN/w of meat extract.

$$TOC_{Val}(\%w/w) = \frac{Carbon\ molar\ mass}{Valine\ molar\ mass} \cdot \frac{\%w_{Val}}{\%w_{meat\ extract}} = \frac{60.05\ mg\ C}{117.15\ mg\ Val} \cdot \frac{3.06\ mg\ Val}{100\ mg\ meat\ extract}$$

$$TOC_{Val}(\%w/w) = \frac{1.57\ mg\ C}{100\ mg\ meat\ extract}$$

$$TN_{Val}(\%w/w) = \frac{Nitrogen\ molar\ mass}{Valine\ molar\ mass} \cdot \frac{\%w_{Val}}{\%w_{meat\ extract}} = \frac{14.01\ mg\ C}{117.15\ mg\ Val} \cdot \frac{3.06\ mg\ Val}{100\ mg\ meat\ extract}$$

$$TN_{Val}(\%w/w) = \frac{0.37\ mg\ C}{100\ mg\ meat\ extract}$$

With the total %w of TOC/w of meat extract (31.51 mgC/100 mg meat extract) and %w of TN/w of meat extract (10.86 mgN/100 mg meat extract) values obtained, theoretical TOC and TN concentrations can be calculated as the sum of the TOC content of the meat extract (1,950 mg/L) and the TOC content of the glycerol ($C_3H_8O_3$) (200 mg/L), and the sum of the TN content of the meat

extract (1,950 mg/L) and the TN content of the ammonium chloride (NH_4Cl) (360 mg/L), respectively, as shown below:

$$TOC(mg\ C/L) = \frac{1950\ mg\ meat\ extract}{L} \cdot \frac{31.51\ mg\ C}{100\ mg\ meat\ extract} + \frac{200\ mg\ C_3H_8O_3}{L} \cdot \frac{36.03\ mg\ C}{92.09\ mg\ C_3H_8O_3}$$

$$TOC(mg\ C/L) = 692.72\ mg\ C/L$$

$$TN(mg\ N/L) = \frac{1950\ mg\ meat\ extract}{L} \cdot \frac{10.86\ mg\ N}{100\ mg\ meat\ extract} + \frac{360\ mg\ NH_4Cl}{L} \cdot \frac{14.01\ mg\ N}{53.49\ mg\ NH_4Cl}$$

$$TN(mg\ N/L) = 305.96\ mg\ N/L$$

Table A.1. Calculations of TOC and TN concentrations of the meat extract based on the information provided by the manufacturer (Oxoid Ltd.).

Symbol	Amino acid	%w/w	Molar mass (g/mol)	Carbon molar mass (g/mol)	Nitrogen molar mass (g/mol)	TOC %w/w	TN %w/w
Ala	Alanine ($C_3H_7NO_2$)	5.85	89.09	36.03	14.01	2.37	0.92
Arg	Arginine ($C_6H_{14}N_4O_2$)	7.10	174.2	72.06	56.03	2.94	2.28
Asp	Aspartic acid ($C_4H_7NO_4$)	5.10	133.1	48.04	14.01	1.84	0.54
Cys	Cysteine ($C_3H_7NO_2S$)	0.68	121.16	36.03	14.01	0.20	0.08
Glu	Glutamic acid ($C_5H_9NO_4$)	10.71	147.13	60.05	14.01	4.37	1.02
Gly	Glycine ($C_2H_5NO_2$)	10.85	75.07	24.02	14.01	3.47	2.02
Ile	Isoleucine ($C_6H_{13}NO_2$)	3.17	131.17	72.06	14.01	1.74	0.34
Leu	Leucine ($C_6H_{13}NO_2$)	3.15	131.17	72.06	14.01	1.73	0.34
Lys	Lysine ($C_6H_{14}N_2O_2$)	4.78	146.19	72.06	28.01	2.36	0.92
Met	Methionine ($C_5H_{11}NO_2S$)	2.61	149.21	60.05	14.01	1.05	0.25
Phe	Phenylalanine ($C_9H_{11}NO_2$)	2.34	165.19	108.10	14.01	1.53	0.20
Pro	Proline ($C_5H_9NO_2$)	7.79	115.13	60.05	14.01	4.06	0.95
Ser	Serine ($C_3H_7NO_3$)	1.87	105.09	36.03	14.01	0.64	0.25
Thr	Threonine ($C_4H_9NO_3$)	2.54	119.12	48.04	14.01	1.02	0.30
Trp	Tryptophan ($C_{11}H_{12}N_2O_2$)	0.34	204.23	132.12	28.01	0.22	0.05
Tyr	Tyrosine ($C_9H_{11}NO_3$)	0.66	181.19	108.10	14.01	0.39	0.05
Val	Valine ($C_5H_{11}NO_2$)	3.06	117.15	60.05	14.01	1.57	0.37
Total		***72.60***	***2304.59***	***1104.98***	***308.15***	***31.51***	***10.86***

Appendix B. Determination of the Reynolds number

In fluid mechanics, the Reynolds number *Re* is a dimensionless number that gives a measure of the ratio of inertial forces to viscous forces and consequently quantifies the relative importance of these two types of forces for given flow conditions. For flow in a pipe or tube, experimental observations show that for fully developed flow, laminar flow occurs when Re < 2,000, turbulent flow occurs when Re > 4,000, and transient flow occurs when 2,000 < Re < 4,000. For flow in a pipe or tube and in a rectangular duct, the Reynolds number is determined by Equation (3.8). An example of the Reynolds number calculation is described as follows, the rest of calculations are portrayed in Table B.1.

$$Re = \frac{\rho v L}{\mu} = \frac{\rho Q L}{\mu A} \tag{3.8}$$

where,

Re = Reynolds number;

v = mean fluid velocity (m/s);

L = length that the flow is going through or around (diameter of the pipe or tube) (m);

V = volume of the sample (L);

μ = dynamic viscosity of the fluid (for water at 25°C, $\eta = 8.98\times10^{-4}$ kg/m.s);

ρ = density of the fluid (for water at 25°C, $\rho = 1000$ kg/m^3);

Q = volumetric flow rate (m^3/s); and

A = pipe cross-sectional area (m^2).

$$A = \frac{(D_0^2 - D_1^2)\pi}{4} \tag{B.1}$$

where,

D_0 = outer diameter (m);

D_1 = inner diameter (m);

then,

$$A = \frac{(0.080^2 - 0.058^2)\cdot 3.14}{4} = 2.38 \times 10^{-3} m^2 \tag{B.1}$$

$$Q = \frac{11.70\text{mL}}{min} \cdot \frac{1L}{1000mL} \cdot \frac{m^3}{1000L} \cdot \frac{1min}{60s} = 1.95 \times 10^{-7}\, m^3/s$$

$$Re = \frac{\rho QL}{\eta A} = \frac{(1000\ \text{kg/m}^3)(1.95\times10^{-7} m^3/s)(0.080-0.058)}{(8.98\times10^{-4}\ \text{kg}/m.s)\cdot(2.38\times10^{-3} m^2)} = 2.00$$

Table B.1. Reynolds number for different flow rates in the ABR, AS, UV/H_2O_2, and their combination.

Process	Flow rate (mL/min)	L (m)	A (m^2)	Re
ABR	2.93	0.120	0.0150	0.44
	3.34	0.120	0.0150	0.50
	3.75	0.120	0.0150	0.56
	4.50	0.120	0.0150	0.67
	4.68	0.120	0.0150	0.69
	7.50	0.120	0.0150	1.11
	7.80	0.120	0.0150	1.16
	11.70	0.120	0.0150	1.74
Aerobic AS	2.93	0.100	0.0100	0.54
	3.34	0.100	0.0100	0.62
	3.75	0.100	0.0100	0.70
	4.50	0.100	0.0100	0.84
	4.68	0.100	0.0100	0.87
	7.50	0.100	0.0100	1.39
	7.80	0.100	0.0100	1.45
	11.70	0.100	0.0100	2.17
UV/H_2O_2	2.93	0.022	0.0024	0.50
	3.34	0.022	0.0024	0.57
	3.75	0.022	0.0024	0.64
	4.50	0.022	0.0024	0.77
	4.68	0.022	0.0024	0.80
	7.50	0.022	0.0024	1.28
	7.80	0.022	0.0024	1.34
	11.70	0.022	0.0024	2.00
Combined anaerobic-aerobic processes	5.90	0.100	0.0100	1.10
	6.75	0.100	0.0100	1.25
Combined anaerobic-aerobic and UV/H_2O_2 processes	5.90	0.022	0.0024	1.01
	6.75	0.022	0.0024	1.16

Appendix C.Determination of TSS and VSS

TSS and VSS were determined by Equations (3.2) and (3.3) as explained in Section 3.5.3, based on the sections 2540D and 2540E of the *Standard Methods* (APHA, 1998).

$$TSS = \frac{(W_1 - W_2 - W_3)}{V} \tag{3.2}$$

$$VSS = \frac{(W_1 - W_2 - W_3) - (W_4 - W_3)}{V} = TSS - \frac{(W_4 - W_3)}{V} \tag{3.3}$$

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);

W_4 = sum of the weights of the solids of the sample and the dish after burning (mg); and

V = volume of the sample (L).

For example, at a HRT of 7 days and a flow rate of 3.34 mL/min, TSS and VSS of the sludge values were calculated to observe the acclimatization of the microorganisms, as depicted in Table C.1.

Table C.1. Calculation of the concentration of TSS and VSS of sludge in compartment 4 of the ABR process.

Item	Sample Testing	Result in Compartment 4
(1)	Volume of the sample of sludge (mL)	2.0000
(2)	Weight of the filter + container (g)	1.4432
(3)	Weight of the dried filter + container + solids @105°C (g)	1.5046
(4)	Weight of the dried filter + container + solids @550°C (g)	1.4707
(5)	TSS (g) = (3) – (2)	0.0614
(6)	VSS (g) = (5) – (4) + (2)	0.0339
(7)	TSS (mg/L) = 1000000×(5) / (1)	30700
(8)	VSS (mg/L) = 1000000×(6) / (1)	16950

Appendix D. Sample standard deviation and relative error analysis

Each experiment in the present work was replicated three times, and the reported results represent the average value of the collected results. In Chapter 4, error bars depicted in the figures

represent the sample standard deviation (*s*), which was used to analyze the accuracy of an experimental measurement for a finite set of experimental data. *s* was calculated as follows.

$$s = \sqrt{\frac{1}{N-1}\sum_{i=1}^{n}(\chi_i - \bar{\chi})^2} \quad \text{(D.1)}$$

where,

χ_i = observed values of the sample items ($\chi_1, \chi_2, \ldots, \chi_n$);

$\bar{\chi}$ = mean value of the sample observations; and

N = sample size.

Relative error was used to express an accuracy of an acceptable value of the quantity being measured. Relative error could be positive, negative or zero indicating that the measured value is smaller than, greater than, or equal to the mean of a set of data. The lowest average absolute error was used as criterion for the optimization of the total electricity costs and HRT. Relative error can be obtained by Equation (D.2) as shown below.

$$Relative\ error = \frac{\bar{\chi}-\chi}{\chi} \cdot 100\% \quad \text{(D.2)}$$

where,

χ = accepted value; and

$\bar{\chi}$ = mean of a finite set of data.

The non-linear least square function was used to determine the best-fit criterion, which means two sets of data are the most close to each other as expressed in Equation (D.3).

$$Z = \sum_{i=1}^{n}\left[\left(\frac{S_f}{S_0}\right)_{i,experiments} - \left(\frac{S_f}{S_0}\right)_{i,prediction}\right]^2 \quad \text{(D.3)}$$

Appendix E. Raw data

Table E.1. TSS and VSS values of the sludge in the ABR and aerobic AS.

1st Test	18-Oct-11	0		
		Aerobic Sludge		
w1	1.4418	g		weight of Container + Filter empty
w2	1.4645	g		weight of Container + Filter + solids @105
w3	1.4477	g		weight of Container + Filter + solids @550
V	10	mL		
MLSS	0.00227	g/mL	2270	mg/L
MLVSS	0.00168	g/mL	1680	mg/L
Anaerobic Sludge				
w1	1.4312	g		weight of Container + Filter empty
w2	1.4736	g		weight of Container + Filter + solids @105
w3	1.4469	g		weight of Container + Filter + solids @550
V	10	mL		
TSS	0.00424	g/mL	4240	mg/L
VSS	0.00267	g/mL	2670	mg/L
2nd Test	20-Oct-11	2		
			Anaerobic Sludge	
w1	1.4452	g		weight of Container + Filter empty
w2	1.5108	g		weight of Container + Filter + solids @105
w3	1.4711	g		weight of Container + Filter + solids @550
V	5	mL		
TSS	0.01312	g/mL	13120	mg/L
VSS	0.00794	g/mL	7940	mg/L
Chamber 1				
w1	1.4433	g		weight of Container + Filter empty
w2	1.5175	g		weight of Container + Filter + solids @105
w3	1.4726	g		weight of Container + Filter + solids @550
V	5	mL		
TSS	0.01484	g/mL	14840	mg/L
VSS	0.00898	g/mL	8980	mg/L
Chamber 2				

w1	1.4352	g		weight of Container + Filter empty
w2	1.5114	g		weight of Container + Filter + solids @105
w3	1.4663	g		weight of Container + Filter + solids @550
V	5	mL		
TSS	0.01524	g/mL	15240	mg/L
VSS	0.00902	g/mL	9020	mg/L
Chamber 3				
w1	1.449	g		weight of Container + Filter empty
w2	1.5169	g		weight of Container + Filter + solids @105
w3	1.4716	g		weight of Container + Filter + solids @550
V	5	mL		
TSS	0.01358	g/mL	13580	mg/L
VSS	0.00906	g/mL	9060	mg/L
Chamber 4				
w1	1.429	g		weight of Container + Filter empty
w2	1.5087	g		weight of Container + Filter + solids @105
w3	1.4647	g		weight of Container + Filter + solids @550
V	5	mL		
TSS	0.01594	g/mL	15940	mg/L
VSS	0.0088	g/mL	8800	mg/L
Chamber 5				
w1	1.4368	g		weight of Container + Filter empty
w2	1.5175	g		weight of Container + Filter + solids @105
w3	1.4752	g		weight of Container + Filter + solids @550
V	5	mL		
TSS	0.01614	g/mL	16140	mg/L
VSS	0.00846	g/mL	8460	mg/L
3rd Test	22-Oct-11	4		
Chamber 1				
w1	1.4378	g		weight of Container + Filter empty
w2	1.5779	g		weight of Container + Filter + solids @105
w3	1.5017	g		weight of Container + Filter + solids @550
V	5	mL		
TSS	0.02802	g/mL	28020	mg/L
VSS	0.01524	g/mL	15240	mg/L

Chamber 2				
w1	1.4332	g		weight of Container + Filter empty
w2	1.5747	g		weight of Container + Filter + solids @105
w3	1.4999	g		weight of Container + Filter + solids @550
V	5	mL		
TSS	0.0283	g/mL	28300	mg/L
VSS	0.01496	g/mL	14960	mg/L
Chamber 3				
w1	1.4339	g		weight of Container + Filter empty
w2	1.5531	g		weight of Container + Filter + solids @105
w3	1.4946	g		weight of Container + Filter + solids @550
V	5	mL		
TSS	0.02384	g/mL	23840	mg/L
VSS	0.0117	g/mL	11700	mg/L
Chamber 4				
w1	1.4434	g		weight of Container + Filter empty
w2	1.5824	g		weight of Container + Filter + solids @105
w3	1.5101	g		weight of Container + Filter + solids @550
V	5	mL		
TSS	0.0278	g/mL	27800	mg/L
VSS	0.01446	g/mL	14460	mg/L
Chamber 5				
w1	1.431	g		weight of Container + Filter empty
w2	1.5793	g		weight of Container + Filter + solids @105
w3	1.5072	g		weight of Container + Filter + solids @550
V	5	mL		
TSS	0.02966	g/mL	29660	mg/L
VSS	0.01442	g/mL	14420	mg/L
4th Test	27-Oct-11	9		
Chamber 1				
w1	1.4395	g		weight of Container + Filter empty
w2	1.5027	g		weight of Container + Filter + solids @105
w3	1.4685	g		weight of Container + Filter + solids @550
V	2	mL		

TSS	0.0316	g/mL	31600	mg/L
VSS	0.0171	g/mL	17100	mg/L

Chamber 2

w1	1.4326	g	weight of Container + Filter empty
w2	1.4841	g	weight of Container + Filter + solids @105
w3	1.4556	g	weight of Container + Filter + solids @550
V	2	mL	

TSS	0.02575	g/mL	25750	mg/L
VSS	0.01425	g/mL	14250	mg/L

Chamber 3

w1	1.4398	g	weight of Container + Filter empty
w2	1.5151	g	weight of Container + Filter + solids @105
w3	1.4763	g	weight of Container + Filter + solids @550
V	2	mL	

TSS	0.03765	g/mL	37650	mg/L
VSS	0.0194	g/mL	19400	mg/L

Chamber 4

w1	1.4432	g	weight of Container + Filter empty
w2	1.5046	g	weight of Container + Filter + solids @105
w3	1.4707	g	weight of Container + Filter + solids @550
V	2	mL	

TSS	0.0307	g/mL	30700	mg/L
VSS	0.01695	g/mL	16950	mg/L

Chamber 5

w1	1.4332	g	weight of Container + Filter empty
w2	1.5073	g	weight of Container + Filter + solids @105
w3	1.4698	g	weight of Container + Filter + solids @550
V	2	mL	

TSS	0.03705	g/mL	37050	mg/L
VSS	0.01875	g/mL	18750	mg/L

5th Test	31-Oct-11	13

Chamber 1

w1	1.4484	g	weight of Container + Filter empty
w2	1.4937	g	weight of Container + Filter + solids @105
w3	1.4679	g	weight of Container + Filter + solids @550

V	2	mL		
TSS	0.02265	g/mL	22650	mg/L
VSS	0.0129	g/mL	12900	mg/L
Chamber 2				
w1	1.4349	g		weight of Container + Filter empty
w2	1.4838	g		weight of Container + Filter + solids @105
w3	1.4563	g		weight of Container + Filter + solids @550
V	2	mL		
TSS	0.02445	g/mL	24450	mg/L
VSS	0.01375	g/mL	13750	mg/L
Chamber 3				
w1	1.4361	g		weight of Container + Filter empty
w2	1.4993	g		weight of Container + Filter + solids @105
w3	1.4663	g		weight of Container + Filter + solids @550
V	2	mL		
TSS	0.0316	g/mL	31600	mg/L
VSS	0.0165	g/mL	16500	mg/L
Chamber 4				
w1	1.4458	g		weight of Container + Filter empty
w2	1.4845	g		weight of Container + Filter + solids @105
w3	1.4609	g		weight of Container + Filter + solids @550
V	2	mL		
TSS	0.01935	g/mL	19350	mg/L
VSS	0.0118	g/mL	11800	mg/L
Chamber 5				
w1	1.4373	g		weight of Container + Filter empty
w2	1.4828	g		weight of Container + Filter + solids @105
w3	1.4592	g		weight of Container + Filter + solids @550
V	2	mL		
TSS	0.02275	g/mL	22750	mg/L
VSS	0.0118	g/mL	11800	mg/L
6th Test	02-Nov-11	15		
Chamber 1				
w1	1.4422	g		weight of Container + Filter empty

w2	1.4700	g		weight of Container + Filter + solids @105
w3	1.4521	g		weight of Container + Filter + solids @550
V	2	mL		
TSS	0.0139	g/mL	13900	mg/L
VSS	0.00895	g/mL	8950	mg/L
Chamber 2				
w1	1.4378	g		weight of Container + Filter empty
w2	1.4893	g		weight of Container + Filter + solids @105
w3	1.4582	g		weight of Container + Filter + solids @550
V	2	mL		
TSS	0.02575	g/mL	25750	mg/L
VSS	0.01555	g/mL	15550	mg/L
Chamber 3				
w1	1.4342	g		weight of Container + Filter empty
w2	1.4707	g		weight of Container + Filter + solids @105
w3	1.4483	g		weight of Container + Filter + solids @550
V	2	mL		
TSS	0.01825	g/mL	18250	mg/L
VSS	0.0112	g/mL	11200	mg/L
Chamber 4				
w1	1.4369	g		weight of Container + Filter empty
w2	1.4721	g		weight of Container + Filter + solids @105
w3	1.4501	g		weight of Container + Filter + solids @550
V	2	mL		
TSS	0.0176	g/mL	17600	mg/L
VSS	0.011	g/mL	11000	mg/L
Chamber 5				
w1	1.4323	g		weight of Container + Filter empty
w2	1.4796	g		weight of Container + Filter + solids @105
w3	1.4534	g		weight of Container + Filter + solids @550
V	2	mL		
TSS	0.02365	g/mL	23650	mg/L
VSS	0.0131	g/mL	13100	mg/L
7th Test	03-Nov-11	16		

Chamber 1

w1	1.451	g		weight of Container + Filter empty
w2	1.4709	g		weight of Container + Filter + solids @105
w3	1.4569	g		weight of Container + Filter + solids @550
V	2	mL		
TSS	0.00995	g/mL	9950	mg/L
VSS	0.007	g/mL	7000	mg/L

Chamber 2

w1	1.4338	g		weight of Container + Filter empty
w2	1.4564	g		weight of Container + Filter + solids @105
w3	1.4415	g		weight of Container + Filter + solids @550
V	2	mL		
TSS	0.0113	g/mL	11300	mg/L
VSS	0.00745	g/mL	7450	mg/L

Chamber 3

w1	1.4347	g		weight of Container + Filter empty
w2	1.4743	g		weight of Container + Filter + solids @105
w3	1.4501	g		weight of Container + Filter + solids @550
V	2	mL		
TSS	0.0198	g/mL	19800	mg/L
VSS	0.0121	g/mL	12100	mg/L

Chamber 4

w1	1.4325	g		weight of Container + Filter empty
w2	1.4658	g		weight of Container + Filter + solids @105
w3	1.4452	g		weight of Container + Filter + solids @550
V	2	mL		
TSS	0.01665	g/mL	16650	mg/L
VSS	0.0103	g/mL	10300	mg/L

Chamber 5

w1	1.4335	g		weight of Container + Filter empty
w2	1.4838	g		weight of Container + Filter + solids @105
w3	1.455	g		weight of Container + Filter + solids @550
V	2	mL		
TSS	0.02515	g/mL	25150	mg/L
VSS	0.0144	g/mL	14400	mg/L

8th Test	05-Nov-11	18		
Chamber 1				
w1	1.4327	g	weight of Container + Filter empty	
w2	1.4692	g	weight of Container + Filter + solids @105	
w3	1.445	g	weight of Container + Filter + solids @550	
V	3	mL		
TSS	0.0122	g/mL	12167	mg/L
VSS	0.0081	g/mL	8067	mg/L
Chamber 2				
w1	1.448	g	weight of Container + Filter empty	
w2	1.5216	g	weight of Container + Filter + solids @105	
w3	1.4762	g	weight of Container + Filter + solids @550	
V	5	mL		
TSS	0.01472	g/mL	14720	mg/L
VSS	0.00908	g/mL	9080	mg/L
Chamber 3				
w1	1.4421	g	weight of Container + Filter empty	
w2	1.4926	g	weight of Container + Filter + solids @105	
w3	1.4614	g	weight of Container + Filter + solids @550	
V	2	mL		
TSS	0.02525	g/mL	25250	mg/L
VSS	0.0156	g/mL	15600	mg/L
Chamber 4				
w1	1.4348	g	weight of Container + Filter empty	
w2	1.4778	g	weight of Container + Filter + solids @105	
w3	1.4506	g	weight of Container + Filter + solids @550	
V	3	mL		
TSS	0.0143	g/mL	14333	mg/L
VSS	0.0091	g/mL	9067	mg/L
Chamber 5				
w1	1.4403	g	weight of Container + Filter empty	
w2	1.4885	g	weight of Container + Filter + solids @105	
w3	1.4601	g	weight of Container + Filter + solids @550	
V	2	mL		
TSS	0.0241	g/mL	24100	mg/L
VSS	0.0142	g/mL	14200	mg/L

Chamber 4				
w1	1.4432	g	weight of Container + Filter empty	
w2	1.5046	g	weight of Container + Filter + solids @105	
w3	1.4707	g	weight of Container + Filter + solids @550	
V	2	mL		
TSS	0.0307	g/mL	30700	mg/L
VSS	0.01695	g/mL	16950	mg/L
9th Test	08-Nov-11	21		
Chamber 1				
w1	1.4316	g	weight of Container + Filter empty	
w2	1.4767	g	weight of Container + Filter + solids @105	
w3	1.447	g	weight of Container + Filter + solids @550	
V	3	mL		
TSS	0.015033333	g/mL	15033	mg/L
VSS	0.0099	g/mL	9900	mg/L
Chamber 2				
w1	1.4309	g	weight of Container + Filter empty	
w2	1.5185	g	weight of Container + Filter + solids @105	
w3	1.4648	g	weight of Container + Filter + solids @550	
V	5	mL		
TSS	0.01752	g/mL	17520	mg/L
VSS	0.01074	g/mL	10740	mg/L
Chamber 3				
w1	1.4438	g	weight of Container + Filter empty	
w2	1.4916	g	weight of Container + Filter + solids @105	
w3	1.4617	g	weight of Container + Filter + solids @550	
V	2	mL		
TSS	0.0239	g/mL	23900	mg/L
VSS	0.01495	g/mL	14950	mg/L

Chamber 4				
w1	1.4377	g		weight of Container + Filter empty
w2	1.5114	g		weight of Container + Filter + solids @105
w3	1.4659	g		weight of Container + Filter + solids @550
V	4	mL		
TSS	0.018425	g/mL	18425	mg/L
VSS	0.011375	g/mL	11375	mg/L
Chamber 5				
w1	1.4337	g		weight of Container + Filter empty
w2	1.5025	g		weight of Container + Filter + solids @105
w3	1.462	g		weight of Container + Filter + solids @550
V	4	mL		
TSS	0.0172	g/mL	17200	mg/L
VSS	0.010125	g/mL	10125	mg/L
10th Test	09-Nov-11	22		
Chamber 1				
w1	1.4394	g		weight of Container + Filter empty
w2	1.4725	g		weight of Container + Filter + solids @105
w3	1.4498	g		weight of Container + Filter + solids @550
V	2	mL		
TSS	0.01655	g/mL	16550	mg/L
VSS	0.01135	g/mL	11350	mg/L
Chamber 2				
w1	1.4302	g		weight of Container + Filter empty
w2	1.4666	g		weight of Container + Filter + solids @105
w3	1.4439	g		weight of Container + Filter + solids @550
V	2	mL		
TSS	0.0182	g/mL	18200	mg/L
VSS	0.01135	g/mL	11350	mg/L
Chamber 3				
w1	1.4427	g		weight of Container + Filter empty
w2	1.4797	g		weight of Container + Filter + solids @105
w3	1.4559	g		weight of Container + Filter + solids @550
V	2	mL		

TSS	0.0185	g/mL	18500	mg/L
VSS	0.0119	g/mL	11900	mg/L

Chamber 4

w1	1.433	g	weight of Container + Filter empty
w2	1.4827	g	weight of Container + Filter + solids @105
w3	1.4512	g	weight of Container + Filter + solids @550
V	2	mL	

TSS	0.02485	g/mL	24850	mg/L
VSS	0.01575	g/mL	15750	mg/L

Chamber 5

w1	1.4299	g	weight of Container + Filter empty
w2	1.4667	g	weight of Container + Filter + solids @105
w3	1.4439	g	weight of Container + Filter + solids @550
V	2	mL	

TSS	0.0184	g/mL	18400	mg/L
VSS	0.0114	g/mL	11400	mg/L

11th Test	10-Nov-11	23		
Chamber 1				
w1	1.4353	g	weight of Container + Filter empty	
w2	1.4903	g	weight of Container + Filter + solids @105	
w3	1.4533	g	weight of Container + Filter + solids @550	
V	3	mL		
TSS	0.018333333	g/mL	18333	mg/L
VSS	0.012333333	g/mL	12333	mg/L

Chamber 2

w1	1.4347	g	weight of Container + Filter empty	
w2	1.4761	g	weight of Container + Filter + solids @105	
w3	1.4491	g	weight of Container + Filter + solids @550	
V	3	mL		
TSS	0.0138	g/mL	13800	mg/L
VSS	0.009	g/mL	9000	mg/L

Chamber 3

w1	1.4303	g	weight of Container + Filter empty
w2	1.4718	g	weight of Container + Filter + solids @105
w3	1.4458	g	weight of Container + Filter + solids @550

V	3	mL		
TSS	0.013833333	g/mL	13833.33333	mg/L
VSS	0.008666667	g/mL	8666.666667	mg/L
Chamber 4				
w1	1.4476	g	weight of Container + Filter empty	
w2	1.4958	g	weight of Container + Filter + solids @105	
w3	1.4656	g	weight of Container + Filter + solids @550	
V	3	mL		
TSS	0.016066667	g/mL	16066.66667	mg/L
VSS	0.010066667	g/mL	10066.66667	mg/L
Chamber 5				
w1	1.4448	g	weight of Container + Filter empty	
w2	1.5209	g	weight of Container + Filter + solids @105	
w3	1.4746	g	weight of Container + Filter + solids @550	
V	3	mL		
TSS	0.025366667	g/mL	25366.66667	mg/L
VSS	0.015433333	g/mL	15433.33333	mg/L

12th Test	11-Nov-11	24			
Chamber 1					
w1	1.4332	g		weight of Container + Filter empty	
w2	1.4741	g		weight of Container + Filter + solids @105	
w3	1.4454	g		weight of Container + Filter + solids @550	
V	3	mL			
TSS	0.013633333	g/mL	13633	mg/L	
VSS	0.009566667	g/mL	9567	mg/L	
Chamber 2					
w1	1.4351	g		weight of Container + Filter empty	
w2	1.4618	g		weight of Container + Filter + solids @105	
w3	1.4431	g		weight of Container + Filter + solids @550	
V	3	mL			
TSS	0.0089	g/mL	8900	mg/L	
VSS	0.006233333	g/mL	6233.333333	mg/L	
Chamber 3					
w1	1.44	g		weight of Container + Filter empty	

w2	1.4645	g		weight of Container + Filter + solids @105
w3	1.4478	g		weight of Container + Filter + solids @550
V	3	mL		
TSS	0.008166667	g/mL	8166.666667	mg/L
VSS	0.005566667	g/mL	5566.666667	mg/L

Chamber 4

w1	1.4368	g		weight of Container + Filter empty
w2	1.4642	g		weight of Container + Filter + solids @105
w3	1.4461	g		weight of Container + Filter + solids @550
V	3	mL		
TSS	0.009133333	g/mL	9133.333333	mg/L
VSS	0.006033333	g/mL	6033.333333	mg/L

Chamber 5

w1	1.445	g		weight of Container + Filter empty
w2	1.4908	g		weight of Container + Filter + solids @105
w3	1.462	g		weight of Container + Filter + solids @550
V	3	mL		
TSS	0.015266667	g/mL	15266.66667	mg/L
VSS	0.0096	g/mL	9600	mg/L

13th Test	17-Nov-11	30		

Chamber 1

w1	1.4307	g		weight of Container + Filter empty
w2	1.4868	g		weight of Container + Filter + solids @105
w3	1.4465	g		weight of Container + Filter + solids @550
V	5	mL		
TSS	0.01122	g/mL	11220	mg/L
VSS	0.00806	g/mL	8060	mg/L

Chamber 2

w1	1.4368	g		weight of Container + Filter empty
w2	1.4926	g		weight of Container + Filter + solids @105
w3	1.4557	g		weight of Container + Filter + solids @550
V	5	mL		
TSS	0.01116	g/mL	11160	mg/L
VSS	0.00738	g/mL	7380	mg/L

Chamber 3				
w1	1.4371	g		weight of Container + Filter empty
w2	1.4919	g		weight of Container + Filter + solids @105
w3	1.4569	g		weight of Container + Filter + solids @550
V	5	mL		
TSS	0.01096	g/mL	10960	mg/L
VSS	0.007	g/mL	7000	mg/L
Chamber 4				
w1	1.4409	g		weight of Container + Filter empty
w2	1.5004	g		weight of Container + Filter + solids @105
w3	1.4617	g		weight of Container + Filter + solids @550
V	5	mL		
TSS	0.0119	g/mL	11900	mg/L
VSS	0.00774	g/mL	7740	mg/L
Chamber 5				
w1	1.4318	g		weight of Container + Filter empty
w2	1.4673	g		weight of Container + Filter + solids @105
w3	1.4438	g		weight of Container + Filter + solids @550
V	2	mL		
TSS	0.01775	g/mL	17750	mg/L
VSS	0.01175	g/mL	11750	mg/L
14th Test	24-Nov-11	37		
Chamber 1				
w1	2.1842	g		weight of Container + Filter empty
w2	2.3144	g		weight of Container + Filter + solids @105
w3	2.2198	g		weight of Container + Filter + solids @550
V	10	mL		
TSS	0.01302	g/mL	13020	mg/L
VSS	0.00946	g/mL	9460	mg/L
Chamber 2				
w1	2.1656	g		weight of Container + Filter empty
w2	2.325	g		weight of Container + Filter + solids @105
w3	2.2385	g		weight of Container + Filter + solids @550
V	10	mL		
TSS	0.01594	g/mL	15940	mg/L

VSS	0.00865	g/mL	8650	mg/L
Chamber 3				
w1	2.187	g		weight of Container + Filter empty
w2	2.301	g		weight of Container + Filter + solids @105
w3	2.2022	g		weight of Container + Filter + solids @550
V	10	mL		
TSS	0.0114	g/mL	11400	mg/L
VSS	0.0099	g/mL	9880	mg/L
Chamber 4				
w1	2.1789	g		weight of Container + Filter empty
w2	2.3024	g		weight of Container + Filter + solids @105
w3	2.2105	g		weight of Container + Filter + solids @550
V	10	mL		
TSS	0.0124	g/mL	12350	mg/L
VSS	0.0092	g/mL	9190	mg/L
Chamber 5				
w1	1.441	g		weight of Container + Filter empty
w2	1.5004	g		weight of Container + Filter + solids @105
w3	1.4652	g		weight of Container + Filter + solids @550
V	3	mL		
TSS	0.0198	g/mL	19800	mg/L
VSS	0.011733333	g/mL	11733.33333	mg/L
15th Test	29-Nov-11	42		
Chamber 1				
w1	2.1584	g		weight of Container + Filter empty
w2	2.2914	g		weight of Container + Filter + solids @105
w3	2.1925	g		weight of Container + Filter + solids @550
V	10	mL		
TSS	0.0133	g/mL	13300	mg/L
VSS	0.0099	g/mL	9890	mg/L
Chamber 2				
w1	2.1992	g		weight of Container + Filter empty
w2	2.3658	g		weight of Container + Filter + solids @105
w3	2.2556	g		weight of Container + Filter + solids @550
V	10	mL		

TSS	0.0167	g/mL	16660	mg/L
VSS	0.0110	g/mL	11020	mg/L

Chamber 3

w1	2.194	g	weight of Container + Filter empty
w2	2.4528	g	weight of Container + Filter + solids @105
w3	2.2922	g	weight of Container + Filter + solids @550
V	12	mL	

TSS	0.0216	g/mL	21566.66667	mg/L
VSS	0.0134	g/mL	13383.33333	mg/L

Chamber 4

w1	2.1933	g	weight of Container + Filter empty
w2	2.3313	g	weight of Container + Filter + solids @105
w3	2.2258	g	weight of Container + Filter + solids @550
V	12	mL	

TSS	0.0115	g/mL	11500	mg/L
VSS	0.0088	g/mL	8791.666667	mg/L

Chamber 5

w1	2.1974	g	weight of Container + Filter empty
w2	2.259	g	weight of Container + Filter + solids @105
w3	2.2212	g	weight of Container + Filter + solids @550
V	3	mL	

TSS	0.0205	g/mL	20533.33333	mg/L
VSS	0.0126	g/mL	12600	mg/L

16th Test	02-Dec-11	45		

Chamber 1

w1	2.179	g	weight of Container + Filter empty
w2	2.2851	g	weight of Container + Filter + solids @105
w3	2.2065	g	weight of Container + Filter + solids @550
V	6	mL	

TSS	0.0177	g/mL	17683	mg/L
VSS	0.0131	g/mL	13100	mg/L

Chamber 2

w1	2.1844	g	weight of Container + Filter empty
w2	2.3081	g	weight of Container + Filter + solids @105

w3	2.2266	g		weight of Container + Filter + solids @550
V	8	mL		
TSS	0.0155	g/mL	15462.5	mg/L
VSS	0.0102	g/mL	10187.5	mg/L
Chamber 3				
w1	2.1787	g		weight of Container + Filter empty
w2	2.2859	g		weight of Container + Filter + solids @105
w3	2.2194	g		weight of Container + Filter + solids @550
V	5	mL		
TSS	0.0214	g/mL	21440	mg/L
VSS	0.0133	g/mL	13300	mg/L
Chamber 4				
w1	2.1765	g		weight of Container + Filter empty
w2	2.2737	g		weight of Container + Filter + solids @105
w3	2.1928	g		weight of Container + Filter + solids @550
V	10	mL		
TSS	0.0097	g/mL	9720	mg/L
VSS	0.0081	g/mL	8090	mg/L
Chamber 5				
w1	2.1926	g		weight of Container + Filter empty
w2	2.2961	g		weight of Container + Filter + solids @105
w3	2.2316	g		weight of Container + Filter + solids @550
V	5	mL		
TSS	0.0207	g/mL	20700	mg/L
VSS	0.0129	g/mL	12900	mg/L
17th Test	09-Dec-11	52		
Chamber 1				
w1	1.3995	g		weight of Container + Filter empty
w2	1.4561	g		weight of Container + Filter + solids @105
w3	1.415	g		weight of Container + Filter + solids @550
V	3	mL		
TSS	0.0189	g/mL	18867	mg/L
VSS	0.0137	g/mL	13700	mg/L
Chamber 2				

w1	1.3858	g		weight of Container + Filter empty
w2	1.4493	g		weight of Container + Filter + solids @105
w3	1.4081	g		weight of Container + Filter + solids @550
V	4	mL		
TSS	0.0159	g/mL	15875	mg/L
VSS	0.0103	g/mL	10300	mg/L
Chamber 3				
w1	1.383	g		weight of Container + Filter empty
w2	1.4181	g		weight of Container + Filter + solids @105
w3	1.3935	g		weight of Container + Filter + solids @550
V	2	mL		
TSS	0.0176	g/mL	17550	mg/L
VSS	0.0123	g/mL	12300	mg/L
Chamber 4				
w1	1.3906	g		weight of Container + Filter empty
w2	1.4103	g		weight of Container + Filter + solids @105
w3	1.3964	g		weight of Container + Filter + solids @550
V	2	mL		
TSS	0.0099	g/mL	9850	mg/L
VSS	0.0070	g/mL	6950	mg/L
Chamber 5				
w1	1.3914	g		weight of Container + Filter empty
w2	1.4447	g		weight of Container + Filter + solids @105
w3	1.411	g		weight of Container + Filter + solids @550
V	3	mL		
TSS	0.0178	g/mL	17766.66667	mg/L
VSS	0.0112	g/mL	11233.33333	mg/L
18th Test	17-Dec-11	60		
Chamber 1				
w1	1.3658	g		weight of Container + Filter empty
w2	1.4459	g		weight of Container + Filter + solids @105
w3	1.3926	g		weight of Container + Filter + solids @550
V	4	mL		
TSS	0.0200	g/mL	20025	mg/L
VSS	0.0133	g/mL	13325	mg/L

Chamber 2

w1	1.3849	g		weight of Container + Filter empty
w2	1.4535	g		weight of Container + Filter + solids @105
w3	1.4073	g		weight of Container + Filter + solids @550
V	4	mL		
TSS	0.0172	g/mL	17150	mg/L
VSS	0.0116	g/mL	11550	mg/L

Chamber 3

w1	1.3899	g		weight of Container + Filter empty
w2	1.4331	g		weight of Container + Filter + solids @105
w3	1.4008	g		weight of Container + Filter + solids @550
V	2	mL		
TSS	0.0216	g/mL	21600	mg/L
VSS	0.0162	g/mL	16150	mg/L

Chamber 4

w1	1.4002	g		weight of Container + Filter empty
w2	1.4257	g		weight of Container + Filter + solids @105
w3	1.4045	g		weight of Container + Filter + solids @550
V	2	mL		
TSS	0.0128	g/mL	12750	mg/L
VSS	0.0106	g/mL	10600	mg/L

Chamber 5

w1	1.3996	g		weight of Container + Filter empty
w2	1.4463	g		weight of Container + Filter + solids @105
w3	1.4108	g		weight of Container + Filter + solids @550
V	3	mL		
TSS	0.0156	g/mL	15567	mg/L
VSS	0.0118	g/mL	11833	mg/L

Table E.2. TSS and VSS values of the sludge in the ABR.

TSS	0	1	2	4	9	13	15	16	18	21	22	23	24	30	37	42	45	52	60
ABR Chamber 1	4240	13120	14840	28020	31600	22650	13900	9950	12167	15033	16550	18333	13633	11220	13020	13300	17683	18867	20025
ABR Chamber 2	4240	13120	15240	28300	25750	24450	25750	11300	14720	17520	18200	13800	8900	11160	15940	16660	15463	15875	17150
ABR Chamber 3	4240	13120	13580	23840	37650	31600	18250	19800	25250	23900	18500	13833	8167	10960	11400	21567	21440	17550	21600
ABR Chamber 4	4240	13120	15940	27800	30700	19350	17600	16650	14333	18425	24850	16067	9133	11900	12350	11500	9720	9850	12750
ABR Chamber 5	4240	13120	16140	29660	37050	22750	23650	25150	24100	17200	18400	25367	15267	17750	19800	20533	20700	17767	15567

VSS	0	1	2	4	9	13	15	16	18	21	22	23	24	30	37	42	45	52	60
ABR Chamber 1	2670	7940	8980	15240	14250	12900	8950	7000	8067	9900	11350	12333	9567	8060	9460	9890	13100	13700	13325
ABR Chamber 2	2670	7940	9020	14960	19400	13750	15550	7450	9080	10740	11350	9000	6233	7380	8650	11020	10188	10300	11550
ABR Chamber 3	2670	7940	9060	11700	16950	16500	11200	12100	15600	14950	11900	8667	5567	7000	9880	13383	13300	12300	16150
ABR Chamber 4	2670	7940	8800	14460	16950	11800	11000	10300	9067	11375	15750	10067	6033	7740	9190	8792	8090	6950	10600
ABR Chamber 5	2670	7940	8460	14420	18750	11800	13100	14400	14200	10125	11400	15433	9600	11750	11733	12600	12900	11233	11833

Table E.3. TSS and VSS values of the sludge in the aerobic AS.

MLSS	0	1	2	4	9	13	15	16	18	21	22	23	24	27	30
Aerobic	2270	4100	4981	8687	9593	6046	5499	5203	5100	4700	4500	3690	3854	3821	3718

MLVSS	0	1	2	4	9	13	15	16	18	21	22	23	24	27	30
Aerobic	1680	2481	2750	4518	5296	3687	3437	3218	2833	2734	2590	2567	2420	2416	2399

Table E.4. pH values of the different processes studied.

Item	0 pH	6 pH	10 pH	12 pH	14 pH	18 pH	19 pH	21 pH	24 pH	28 pH	30 pH	36 pH	39 pH	42 pH	49 pH	60 pH	67 pH	74 pH	81 pH	88 pH	95 pH	102 pH	109 pH	116 pH	123 pH	130 pH	137 pH	144 pH	151 pH	158 pH	165 pH	172 pH	179 pH	186 pH	193 pH	200 pH
SSWW	6.92	6.82	6.86	6.87	6.85	6.92	6.82	6.86	6.87	6.85	6.86	6.87	6.85	6.85	6.86	6.87	6.85	6.87	6.85	6.86	6.87	6.85	6.92	6.82	6.86	6.87	6.85	6.86	6.87	6.85	6.85	6.86	6.87	6.85	6.87	6.85
ABR Chamber 1	6.84	6.57	6.46	6.67	6.94	6.7	6.64	6.83	6.82	6.59	6.7	6.66	6.70	6.47	6.62	7.00	6.70	6.77	6.82	6.76	6.79	6.79	6.77	6.82	6.76	6.79	6.79	6.76	6.79	6.79	6.79	6.76	6.79	6.79	6.79	6.79
ABR Chamber 2	6.97	6.54	6.5	6.58	6.93	6.7	6.64	6.83	6.05	6.63	6.84	6.76	6.78	6.75	6.75	6.35	6.62	6.57	6.51	6.56	6.55	6.54	6.57	6.51	6.56	6.55	6.54	6.56	6.55	6.54	6.54	6.56	6.55	6.54	6.55	6.54
ABR Chamber 3	6.99	6.53	6.53	6.64	7.06	6.73	6.58	6.73	6.01	6.71	6.76	6.84	6.84	6.87	6.80	6.79	6.82	6.80	6.80	6.81	6.80	6.81	6.80	6.80	6.81	6.80	6.81	6.81	6.80	6.81	6.81	6.81	6.80	6.81	6.80	6.81
ABR Chamber 4	6.97	6.58	6.55	6.56	7.21	6.68	6.52	6.72	6.77	6.75	6.89	6.88	6.72	6.87	6.82	6.77	6.82	6.80	6.79	6.81	6.80	6.80	6.80	6.79	6.81	6.80	6.80	6.81	6.80	6.80	6.80	6.81	6.80	6.80	6.80	6.80
ABR Chamber 5	7	6.64	6.63	6.75	7.21	6.67	6.5	6.64	6.98	6.7	6.9	6.80	6.79	6.90	6.82	6.02	6.91	6.92	6.95	6.93	6.93	6.94	6.92	6.95	6.93	6.93	6.94	6.93	6.93	6.94	6.94	6.93	6.93	6.94	6.93	6.94
ABR Clarifier	7	6.62	6.58	6.63	7.14	6.67	6.51	6.63	6.97	6.71	6.84	6.85	6.79	6.88	6.81	6.01	6.90	6.91	6.94	6.92	6.92	6.92	6.91	6.94	6.92	6.92	6.92	6.92	6.92	6.92	6.92	6.92	6.92	6.92	6.92	6.92
ABR effluent	7.9	7.43	7.53	7.34	7.7	7.73	7.62	7.73	6.97	7.64	6.89	7.52	6.81	6.88	7.15	7.05	7.03	7.06	7.05	7.05	7.06	7.05	7.06	7.05	7.05	7.06	7.05	7.05	7.06	7.05	7.05	7.05	7.06	7.05	7.06	7.05
Aeration Tank	7.6	7.16	7.81	7.85	7.66	7.74	5.78	6.44	6.77	6.55	6.61	6.92	6.74	7.10	6.78	7.02	6.97	6.92	6.97	6.95	6.95	6.96	6.92	6.97	6.95	6.95	6.96	6.95	6.95	6.96	6.96	6.95	6.95	6.96	6.95	6.96
AS Clarifier	7.38	6.99	7.68	7.8	7.55	7.92	6.9	6.31	6.77	7.27	7.1	6.90	6.92	7.77	7.19	7.00	7.32	7.17	7.16	7.22	7.18	7.19	7.17	7.16	7.22	7.18	7.19	7.22	7.18	7.19	7.19	7.22	7.18	7.19	7.18	7.19
AS effluent	7.55	7.22	7.83	7.98	7.56	7.87	6.85	6.53	6.72	7.35	6.51	7.00	6.80	7.60	7.05	6.95	7.20	7.07	7.07	7.11	7.08	7.09	7.07	7.07	7.11	7.08	7.09	7.11	7.08	7.09	7.09	7.11	7.08	7.09	7.08	7.09
UV/H_2O_2																6.20	6.20	6.20	6.18	6.19	6.20	6.20	6.20	6.18	6.19	6.20	6.20	6.19	6.20	6.20	6.20	6.19	6.20	6.20	6.20	6.20

Table E.5. Temperature values of the different processes studied.

Item	0 Temp (°C)	6 Temp (°C)	10 Temp (°C)	12 Temp (°C)	14 Temp (°C)	18 Temp (°C)	19 Temp (°C)	21 Temp (°C)	24 Temp (°C)	28 Temp (°C)	30 Temp (°C)	36 Temp (°C)	39 Temp (°C)	42 Temp (°C)	49 Temp (°C)	60 Temp (°C)	67 Temp (°C)	74 Temp (°C)	81 Temp (°C)	88 Temp (°C)	95 Temp (°C)	102 Temp (°C)	109 Temp (°C)	116 Temp (°C)	123 Temp (°C)	130 Temp (°C)	137 Temp (°C)	144 Temp (°C)	151 Temp (°C)	158 Temp (°C)	165 Temp (°C)	172 Temp (°C)	179 Temp (°C)	186 Temp (°C)	193 Temp (°C)	200 Temp (°C)
SSW	24.9	24.9	24.8	24.7	24.7	24.80	24.7	24.80	24.80	24.7	24.80	24.7	24.7	24.80	24.80	24.80	24.7	24.80	24.7	24.7	24.80	24.7	24.7	24.80	24.7	24.80	24.7	24.7	24.80	24.7	24.80	24.7	24.80	24.7	24.60
ABR Chamber 1	25.5	24	25.2	24.9	24.9	25.4	25	24.70	24.1	24.8	24.70	24.7	24.6	24.6	24.70	24.8	24.8	24.6	24.6	24.6	24.70	24.6	24.6	24.70	24.6	24.70	24.6	24.6	24.70	24.6	24.70	24.6	24.70	24.6	24.50
ABR Chamber 2	25.7	24.3	24.9	25.1	24.6	25.3	25	24.70	24.3	24.9	24.70	24.7	24.6	24.7	24.70	24.9	24.8	24.7	24.6	24.7	24.70	24.6	24.7	24.70	24.7	24.70	24.7	24.7	24.70	24.7	24.70	24.7	24.70	24.7	24.60
ABR Chamber 3	25.6	24.5	25	24.8	24.9	25.3	25.5	24.70	24.1	24.9	24.70	24.7	24.6	24.6	24.70	24.9	24.8	24.6	24.6	24.6	24.70	24.6	24.6	24.70	24.6	24.70	24.6	24.6	24.70	24.6	24.70	24.6	24.70	24.6	24.50
ABR Chamber 4	25.4	24.4	25.3	24.6	25	25.3	25.2	24.80	24.4	24.9	24.80	24.8	24.7	24.7	24.80	24.9	24.9	24.7	24.7	24.7	24.80	24.7	24.7	24.80	24.7	24.80	24.7	24.7	24.80	24.7	24.80	24.7	24.80	24.7	24.70
ABR Chamber 5	25.3	24.5	25.4	24.5	24.9	25.5	25.3	24.70	24.1	24.9	24.70	24.7	24.6	24.6	24.70	24.9	24.9	24.6	24.6	24.6	24.70	24.6	24.6	24.70	24.6	24.70	24.6	24.6	24.70	24.6	24.70	24.6	24.70	24.6	24.50
ABR Clarifier	25.1	24.5	25.4	24.4	24.8	25.4	25.3	25.00	25.1	24.9	25.00	25.0	24.9	25.0	25.00	24.9	25.0	25.0	24.9	25.0	25.00	24.9	25.0	24.90	25.0	24.90	25.0	25.0	24.90	25.0	24.90	25.0	24.90	25.0	24.90
ABR effluent	25.3	24.6	25.2	24.2	24.8	25.5	24.3	24.60	24.3	24.8	24.60	24.5	24.6	24.6	24.60	24.8	24.7	24.6	24.6	24.6	24.60	24.6	24.6	24.60	24.6	24.60	24.6	24.6	24.60	24.6	24.60	24.6	24.60	24.6	24.60
Aeration Tank	25.6	24.3	25	24.1	25.1	25.4	24.8	24.60	24.3	24.7	24.60	24.5	24.5	24.5	24.60	24.7	24.7	24.5	24.5	24.5	24.60	24.5	24.5	24.50	24.6	24.50	24.5	24.5	24.40	24.5	24.60	24.5	24.60	24.5	24.50
AS Clarifier	25.6	24.4	25.2	24.1	25	25.1	24.4	24.70	24.3	24.8	24.70	24.6	24.6	24.6	24.70	24.8	24.7	24.6	24.6	24.6	24.70	24.6	24.6	24.60	24.6	24.60	24.6	24.6	24.60	24.6	24.60	24.6	24.60	24.6	24.60
AS effluent	25.6	24.6	25.4	24.3	25	25.5	24.5	24.50	24.3	24.8	24.50	24.4	24.4	24.5	24.50	24.8	24.6	24.5	24.4	24.5	24.50	24.4	24.5	24.50	24.5	24.50	24.5	24.5	24.50	24.5	24.50	24.5	24.50	24.5	24.50
UV/H_2O_2																26.5	26.5	26.5	26.4	26.5	26.5	26.4	26.5	26.5	26.5	26.5	26.5	26.5	26.4	26.5	26.6	26.5	26.6	26.5	26.5	26.5

Table E.6. Calculation of the $CBOD_5$ for the different processes studied.

		DO0	DO5	$CBOD_5$	$CBOD_5$ (%)		Vsln (mL)	300
SSWWin		8.49	2.09	640.00		6.40	Vww (mL)	3
UV/H_2O_2		3.42	2.42	100.00	84.38%	1.00		
Aerobic AS		1.49	0.99	50.00	92.19%	0.50		
ABR		0.48	0.17	31.00	95.16%	0.31		
Combined Ana-Ae		1.65	1.61	4.00	99.38%	0.04		
Combined Ae-Ana		0.78	0.75	3.00	99.53%	0.03		
Combined Ana-Ae-UV		2.44	2.42	2.00	99.69%	0.02		
Blank 1		8.60	8.59	1.00				
Blank 2		8.59	8.58	1.00				
	V	DO0 (mg/L)	DO5 (mg/L)	f	SCF (mg/L)	SCF Average*		
Seed 10mL	10	8.42	7.35	0.40	0.43			
Seed 15mL	15	8.50	7.28	0.27	0.33	0.00		
Seed 20mL	20	8.56	6.62	0.20	0.39			
		* Values in the range 0.6 - 1.0 mg/L						
		DO0	DO5					
GGA 1		8.45	6.24					
GGA 2		8.43	6.20					

Table E.7. Calculation of the TOC and TN removal for the different processes studied.

20%		Q	3.34	HRT	7	
	TOC (mg/L)	SD (mg/L)	TOC Removal (%)	TN (mg/L)	SD (mg/L)	TN Removal (%)
dw-1	0.307	0.0575		0.0587	0.0373	
dw-2	0.2251	0.0188		0.0267	0.007	
SSWWin	183.3548	1.2219	0.00%	63.3791	0.3782	0.00%
Ana Chamber 1	71.1603	1.386	61.19%	60.8111	0.559	4.05%
Ana Chamber 2	61.2356	2.1073	66.60%	58.8848	2.0337	7.09%
Ana Chamber 3	58.0253	1.0191	68.35%	54.992	0.7893	13.23%
Ana Chamber 4	54.5	0.8076	70.28%	53.9638	0.8706	14.86%
Ana Chamber 5	51.2816	5.2196	72.03%	46.4038	0.7253	26.78%
Ana Clarifier	49.251	0.6999	73.14%	46.367	1.1157	26.84%
Ana Effluent	29.2356	1.1519	84.06%	43.5296	1.242	31.32%
WWin	183.3548	1.2219	0.00%	63.3791	0.3782	0.00%
Aeration Tank	32.9951	0.9088	82.00%	39.4608	0.1893	37.74%
Ae Clarifier	14.6549	0.4434	92.01%	38.5917	0.8127	39.11%
Ae Effluent	14.4837	0.4042	92.10%	37.2671	1.5777	41.20%

40%		Q	3.34	HRT	7	
	TOC (mg/L)	SD (mg/L)	TOC Removal (%)	TN (mg/L)	SD (mg/L)	TN Removal (%)
dw-1	1.5883	0.081		0.0505	0.009	
dw-2	0.6109	0.0353		0.0279	0.0068	
WWin	366.7096	1.433	0.00%	119.2971	11.1508	0.00%
Ch1	95.7851	2.314	73.88%	79.7571	1.7251	33.14%
Ch2	88.1839	2.5392	75.95%	80.4314	0.3346	32.58%
Ch3	85.3256	0.9968	76.73%	76.6218	1.0736	35.77%
Ch4	83.8272	0.7274	77.14%	73.6	1.7407	38.31%
Ch5	76.858	2.0524	79.04%	71.5846	0.8433	39.99%
Ana1	75.3674	1.7162	79.45%	70.6943	0.3211	40.74%
Ana2	57.8479	0.9428	84.23%	70.5164	0.2795	40.89%
WWin	366.7096	1.433	0.00%	119.2971	11.1508	0.00%
Ae1	51.118	1.2525	86.06%	85.2627	0.4361	28.53%
Ae2	39.4769	1.2938	89.23%	74.4391	0.8182	37.60%
Ae3	28.1867	0.962	92.31%	65.921	3.3638	44.74%

60%		Q	4.68	HRT	5	
	TOC (mg/L)	SD (mg/L)	TOC Removal (%)	TN (mg/L)	SD (mg/L)	TN Removal (%)
dw-1	0.9888	0.0788		0.0366	0.0015	
dw-2	0.3516	0.0592		0.041	0.0005	
WWin	639.4368	1.5522	0.00%	144.4031	1.1447	0.00%
Ch1	233.7442	3.2268	63.45%	111.1064	1.789	23.06%
Ch2	207.4607	5.0784	67.56%	108.4051	0.7053	24.93%
Ch3	182.0629	2.2434	71.53%	107.6782	0.315	25.43%
Ch4	159.6082	2.7466	75.04%	107.4829	0.2214	25.57%
Ch5	159.2885	1.8825	75.09%	107.4829	0.995	25.57%
Ana1	157.2442	1.1014	75.41%	105.1249	0.8626	27.20%
Ana2	104.6063	1.7477	83.64%	91.7067	1.1493	36.49%
WWin	639.4368	1.5522	0.00%	144.4031	1.1447	0.00%
Ae1	116.0401	0.4459	81.85%	137.1057	4.6142	5.05%
Ae2	99.0038	0.8644	84.52%	118.1492	0.4158	18.18%
Ae3	66.1437	1.1189	89.66%	82.0349	0.7712	43.19%

60%		Q	3.34	HRT	7	
	TOC (mg/L)	SD (mg/L)	TOC Removal (%)	TN (mg/L)	SD (mg/L)	TN Removal (%)
dw-1	0.1907	0.0198		0.005	0.0044	
dw-2	0.1894	0.0486		0.0186	0.0062	
WWin	645.6042	13.8694		147.1487	3.4519	
WWin	639.4368	1.5522	0.00%	144.4031	1.1447	0.00%
Ch1	164.816	1.3986	74.22%	109.0119	0.8438	24.51%
Ch2	131.343	1.0813	79.46%	105.463	2.0159	26.97%
Ch3	114.7329	0.66	82.06%	102.5234	5.9991	29.00%
Ch4	90.3126	0.5661	85.88%	100.9901	1.6786	30.06%
Ch5	81.547	0.8644	87.25%	91.0476	0.562	36.95%
Ana1	81.5246	0.4459	87.25%	87.0177	0.1553	39.74%
Ana2	80.4452	1.1189	87.42%	82.9439	0.5151	42.56%
WWin	639.4368	1.5522	0.00%	144.4031	1.1447	0.00%
Ae1	64.804	0.1145	89.87%	100.4628	3.3078	30.43%
Ae2	57.5101	1.0087	91.01%	75.9291	0.3542	47.42%
Ae3	46.9364	0.5914	92.66%	56.935	2.4356	60.57%

60%		Q	2.93	HRT	8	
	TOC (mg/L)	SD (mg/L)	TOC Removal (%)	TN (mg/L)	SD (mg/L)	TN Removal (%)
dw-1	0.2698	0.0447		0.0256	0.0098	
dw-2	0.3718	0.053		0.0556	0.0117	
WWin	645.6042	13.8694		147.1487	3.4519	
WWin	639.4368	1.5522	0.00%	144.4031	1.1447	0.00%
Ch1	156.0451	2.9782	75.60%	78.0504	5.511	45.95%
Ch2	111.0964	1.0001	82.63%	76.6637	5.3279	46.91%
Ch3	94.5914	1.4322	85.21%	75.8312	5.3747	47.49%
Ch4	82.9015	1.222	87.04%	70.5431	4.8112	51.15%
Ch5	77.8824	1.0369	87.82%	70.4414	4.8665	51.22%
Ana1	76.811	1.8813	87.99%	70.0945	4.847	51.46%
Ana2	71.0912	0.6281	88.88%	70.0092	4.2549	51.52%
WWin	639.4368	1.5522	0.00%	144.4031	1.1447	0.00%
Ae1	45.268	0.3181	92.92%	93.3773	3.5302	35.34%
Ae2	40.4147	0.5957	93.68%	69.9532	5.7382	51.56%
Ae3	36.7103	2.4535	94.26%	35.8786	5.7034	75.15%

80%		Q	11.70	HRT	2	
	TOC (mg/L)	SD (mg/L)	TOC Removal (%)	TN (mg/L)	SD (mg/L)	TN Removal (%)
dw-1	1.0075			0.0313		
WWin	733.4193	3.2423	0.00%	181.9955	2.1257	0.00%
Ch1	224.6072	3.2834	69.38%	114.3869	2.805	37.15%
Ch2	158.8953	4.774	78.33%	109.3171	0.806	39.93%
Ch3	128.927	4.304	82.42%	104.9981	0.6585	42.31%
Ch4	114.7546	5.5229	84.35%	104.5505	1.7229	42.55%
Ch5	112.9793	0.7469	84.60%	103.701	0.6884	43.02%
Ana1	109.1723	3.598	85.11%	99.3056	0.6279	45.44%
Ana2	107.9521	3.331	85.28%	97.5862	1.608	46.38%
WWin	733.4193	3.2423	0.00%	181.9955	2.1257	0.00%
Ae1	105.1247	6.4358	85.67%	165.7801	1.312	8.91%
Ae2	91.5973	2.8598	87.51%	123.0281	0.645	32.40%
Ae3	42.9999	2.7138	94.14%	120.9563	1.5302	33.54%

80%		Q	4.68	HRT	5	
	TOC (mg/L)	SD (mg/L)	TOC Removal (%)	TN (mg/L)	SD (mg/L)	TN Removal (%)
dw-1	0.3949	0.0354		0.0216	0.0041	
WWin	733.4193	3.2423	0.00%	181.9955	2.1257	0.00%
Ch1	400.1021	5.849	45.45%	138.5113	3.3977	23.89%
Ch2	353.834	10.633	51.76%	137.969	1.0184	24.19%
Ch3	295.117	9.8539	59.76%	135.0366	0.847	25.80%
Ch4	237.731	11.4415	67.59%	129.1994	2.1291	29.01%
Ch5	188.0034	1.243	74.37%	122.0746	0.8104	32.92%
Ana1	182.0516	6.0007	75.18%	120.8888	0.7644	33.58%
Ana2	129.9731	4.0113	82.28%	104.7248	1.7263	42.46%
WWin	733.4193	3.2423	0.00%	181.9955	2.1257	0.00%
Ae1	86.4916	5.2951	88.21%	133.6378	1.0583	26.57%
Ae2	51.9128	1.6208	92.92%	125.597	0.6589	30.99%
Ae3	41.7024	4.0455	94.31%	115.4007	2.3326	36.59%

80%		Q	3.34	HRT	7	
	TOC (mg/L)	SD (mg/L)	TOC Removal (%)	TN (mg/L)	SD (mg/L)	TN Removal (%)
dw-1	0.415	0.0088		0.0843	0.0038	
WWin	733.4193		0.00%	181.9955		0.00%
Ch1	418.4278	11.2998	42.95%	137.1057	2.2768	24.67%
Ch2	337.03	7.3671	54.05%	134.6899	2.5776	25.99%
Ch3	306.6029	5.7317	58.20%	133.2053	3.5482	26.81%
Ch4	246.4114	3.8294	66.40%	129.5068	2.3276	28.84%
Ch5	205.6607	6.7873	71.96%	123.4488	0.4633	32.17%
Ana1	133.8676	2.732	81.75%	110.3611	1.309	39.36%
Ana2	88.4298	4.0087	87.94%	102.122	2.0679	43.89%
WWin	733.4193		0.00%	181.9955		0.00%
Ae1	98.681	4.5213	86.55%	129.7378	1.3824	28.71%
Ae2	75.6791	1.0401	89.68%	89.9092	1.4468	50.60%
Ae3	40.7836	1.8826	94.44%	57.9372	1.5785	68.17%

100%		Q	7.80	HRT	3	
	TOC (mg/L)	SD (mg/L)	TOC Removal (%)	TN (mg/L)	SD (mg/L)	TN Removal (%)
dw-1	0.3199	0.146		0.0059	0.0239	
WWin	1008.8495	5.1109	0.00%	254.2300	1.5222	0.00%
Ch1	571.8746	20.4354	43.31%	230.5054	2.6292	9.33%
Ch2	454.0111	9.0468	55.00%	228.072	7.9239	10.29%
Ch3	331.6076	6.07	67.13%	216.1698	4.8588	14.97%
Ch4	260.0331	2.8277	74.22%	209.8313	1.9213	17.46%
Ch5	208.7259	8.4141	79.31%	203.4793	6.8815	19.96%
Ana1	218.5146	1.4615	78.34%	145.2086	1.105	42.88%
Ana2	142.9079	1.9412	85.83%	132.9547	1.2708	47.70%
WWin	1008.8495	5.1109	0.00%	254.23	1.5222	0.00%
Ae1	145.7414	1.3337	85.55%	91.6897	7.5438	63.93%
Ae2	118.0836	1.2225	88.30%	80.186	6.7892	68.46%
Ae3	84.0839	1.4456	91.67%	70.1051	8.1143	72.42%

100%		Q	3.34	HRT	7	
	TOC (mg/L)	SD (mg/L)	TOC Removal (%)	TN (mg/L)	SD (mg/L)	TN Removal (%)
dw-1	0.5415	0.0791		0.1862	0.0932	
WWin	1008.8495	5.1109	0.00%	254.2300	1.5222	0.00%
Ch1	578.6266	11.973	42.64%	237.5711	1.685	6.55%
Ch2	420.5742	2.9245	58.31%	231.3608	2.1225	9.00%
Ch3	332.9334	6.2618	67.00%	230.4288	0.9252	9.36%
Ch4	324.5938	2.218	67.83%	153.9032	0.4274	39.46%
Ch5	270.5846	5.9031	73.18%	145.6495	2.0549	42.71%
Ana1	182.3738	1.3889	81.92%	138.1936	1.2589	45.64%
Ana2	106.2775	6.1932	89.47%	127.929	0.9195	49.68%
WWin	1008.8495	5.1109	0.00%	254.23	1.5222	0.00%
Ae1	191.8118	16.6121	80.99%	137.4408	1.0348	45.94%
Ae2	175.4183	1.4543	82.61%	79.3873	8.1796	68.77%
Ae3	55.2232	6.3439	94.53%	67.4811	7.7837	73.46%

100%	Combined	Ana-Ae	Q	7.50	HRT	3.12
	TOC (mg/L)	SD (mg/L)	TOC Removal (%)	TN (mg/L)	SD (mg/L)	TN Removal (%)
dw-1	0.3863	0.0274		0.0083	0.0085	
WWin	1008.8495	5.1109	0.00%	419.7730	1.5222	0.00%
Ch1	721.422	5.1109	28.49%	399.773	1.5222	4.76%
Ch2	520.136	2.878	48.44%	385.371	2.6648	8.20%
Ch3	346.757	4.6709	65.63%	376.954	3.305	10.20%
Ch4	324.384	2.1438	67.85%	364.112	2.9875	13.26%
Ch5	303.9396	2.1095	69.87%	363.676	2.4383	13.36%
Ana1	299.311	2.1356	70.33%	355.758	2.4985	15.25%
Ae1	120.588	0.4762	88.05%	342.048	0.6343	18.52%
Ae2	89.378	0.2583	91.14%	335.293	4.0465	20.13%
Eff	69.1	0.4271	93.15%	280.382	3.4084	33.21%

100%	Combined	Ana-Ae	Q	3.75	HRT	6.24
	TOC (mg/L)	SD (mg/L)	TOC Removal (%)	TN (mg/L)	SD (mg/L)	TN Removal (%)
dw-1	0.5415	0.0791		0.1862	0.0932	
WWin	1008.8495	5.1109	0.00%	419.7730	1.5222	0.00%
Ch1	462.2498	14.6377	54.18%	206.7206	5.5128	50.75%
Ch2	396.839	25.2943	60.66%	197.02	1.4041	53.07%
Ch3	338.2224	8.3264	66.47%	187.412	4.0548	55.35%
Ch4	317.3341	16.4419	68.54%	180.2934	1.7837	57.05%
Ch5	306.1535	9.7634	69.65%	152.517	0.559	63.67%
Ana1	162.7555	2.6058	83.87%	147.0215	1.487	64.98%
Ae1	92.6392	2.0167	90.82%	146.1403	2.9999	65.19%
Ae2	63.1264	0.6222	93.74%	102.5989	1.9791	75.56%
Eff	36.6972	0.7358	96.36%	81.7275	0.6145	80.53%

100%	Combined	Ae-Ana	Q	7.50	HRT	3.12
	TOC (mg/L)	SD (mg/L)	TOC Removal (%)	TN (mg/L)	SD (mg/L)	TN Removal (%)
dw-1	0.2279	0.0352		0.0135	0.0033	
WWin	1008.8495	5.1109	0.00%	425.5423	3.4782	0.00%
Ae1	215.5937	1.402	78.63%	341.4685	7.1308	19.76%
Ae2	177.792	6.3572	82.38%	337.6347	8.3374	20.66%
Ch1	169.0934	4.2979	83.24%	336.0975	7.8471	21.02%
Ch2	161.0194	3.2936	84.04%	334.8627	2.8142	21.31%
Ch3	157.0349	5.6209	84.43%	321.2079	7.0627	24.52%
Ch4	156.8219	4.5948	84.46%	318.6252	4.2298	25.12%
Ch5	148.546	3.771	85.28%	319.486	5.0119	24.92%
Ana	141.1703	2.3643	86.01%	307.1767	4.0528	27.82%
Eff	140.7936	1.696	86.04%	300.3849	3.3672	29.41%

100%	Combined	Ae-Ana	Q	3.75	HRT	6.24
	TOC (mg/L)	SD (mg/L)	TOC Removal (%)	TN (mg/L)	SD (mg/L)	TN Removal (%)
dw-1	0.2279	0.0352		0.0135	0.0033	
WWin	1008.8495	5.1109	0.00%	425.5423	3.4782	0.00%
Ae1	204.4599	1.402	79.73%	181.7377	7.1308	57.29%
Ae2	168.8271	6.3572	83.27%	149.9653	8.3374	64.76%
Ch1	151.352	4.2979	85.00%	139.2546	7.8471	67.28%
Ch2	150.31	3.2936	85.10%	128.6837	2.8142	69.76%
Ch3	149.645	5.6209	85.17%	122.3708	7.0627	71.24%
Ch4	149.4387	4.5948	85.19%	121.1771	4.2298	71.52%
Ch5	100.3359	3.771	90.05%	116.9516	5.0119	72.52%
Ana	60.5536	2.3643	94.00%	102.9395	4.0528	75.81%
Eff	39.3044	1.696	96.10%	100.262	3.3672	76.44%

100%	Combined	Ana-Ae-UV	Q	7.50	HRT	3.15
	TOC (mg/L)	SD (mg/L)	TOC Removal (%)	TN (mg/L)	SD (mg/L)	TN Removal (%)
dw-1	0.0925	0.2671		0.0135	0.0033	
WWin	941.1858	12.8471	0.00%	214.0842	13.4782	0.00%
Ch1	469.4826	11.3591	50.12%	150.9275	7.1308	29.50%
Ch2	298.0182	16.5156	68.34%	101.4802	8.3374	52.60%
Ch3	230.4414	14.4603	75.52%	95.0801	7.8471	55.59%
Ch4	188.5857	6.3111	79.96%	91.4496	2.8142	57.28%
Ch5	164.1492	4.5808	82.56%	78.2836	1.0627	63.43%
Ana	154.9005	6.1319	83.54%	77.1396	1.2298	63.97%
Ae1	93.0076	1.2746	90.12%	49.9809	1.0119	76.65%
Ae2	92.43	1.4623	90.18%	41.0115	1.0528	80.84%
UV	11.5326	0.1266	98.77%	40.7754	0.3672	80.95%
Eff	10.3053	0.1518	98.91%	40.621	0.2849	81.03%

100%	Combined	Ana-Ae-UV	Q	6.75	HRT	3.50
	TOC (mg/L)	SD (mg/L)	TOC Removal (%)	TN (mg/L)	SD (mg/L)	TN Removal (%)
dw-1	0.0925	0.2671		0.0135	0.0033	
WWin	1006.8993	10.0131	0.00%	203.8395	11.024	0.00%
Ch1	460.5657	10.0259	51.07%	155.7064	11.135	27.27%
Ch2	296.4317	13.5481	68.50%	102.1924	11.3362	52.27%
Ch3	224.9815	12.4857	76.10%	98.5308	5.3731	53.98%
Ch4	181.3605	8.9379	80.73%	84.4567	2.7559	60.55%
Ch5	161.8782	8.1521	82.80%	79.0176	5.8599	63.09%
Ana	154.1284	8.0405	83.62%	74.8635	3.097	65.03%
Ae1	83.7288	2.9675	91.10%	46.6171	2.668	78.22%
Ae2	81.8802	2.4493	91.30%	37.9036	0.7882	82.30%
UV	8.5292	0.5251	99.09%	37.4527	0.481	82.51%
Eff	8.1433	0.3207	99.13%	37.436	0.2816	82.51%

100%	Combined	Ana-Ae-UV	Q	5.90	HRT	4.00
	TOC (mg/L)	SD (mg/L)	TOC Removal (%)	TN (mg/L)	SD (mg/L)	TN Removal (%)
dw-1	0.0925	0.2671		0.0135	0.0033	
WWin	1004.8855	10.0131	0.00%	200.0294	10.034	0.00%
Ch1	454.5485	10.0259	51.70%	152.796	12.135	28.63%
Ch2	295.8308	13.5481	68.57%	100.2822	13.3362	53.16%
Ch3	214.4315	12.4857	77.22%	96.6891	5.3731	54.84%
Ch4	180.8297	8.9379	80.79%	82.878	3.7559	61.29%
Ch5	158.4044	8.1521	83.17%	77.5407	5.89	63.78%
Ana	153.6721	8.0405	83.67%	73.4642	3.097	65.68%
Ae1	83.5613	2.9675	91.12%	45.7458	2.668	78.63%
Ae2	81.7164	2.4493	91.32%	37.1951	0.7882	82.63%
UV	0.1825	0.1305	99.98%	36.7527	0.481	82.83%
Eff	0.1682	0.028	99.98%	36.7363	0.216	82.84%

Table E.8. Maximum values of TOC and TN removal for the different processes studied.

	[TN] (mg/L)	[TOC] (mg/L)
SSWW	425.5423	1008.8495
ABR	214.1337	106.2775
Aerobic AS	112.9531	50.12
Combined Ae-Ana	100.262	39.3044
Combined Ana-Ae	82.8508	36.6972
Combined Ana-Ae-UV	78.1527	0.1689
	%TN Removal	**%TOC Removal**
UV/H_2O_2	5.99%	75.22%
ABR	49.68%	89.47%
Aerobic AS	73.46%	94.53%
Combined Ae-Ana	76.44%	96.10%
Combined Ana-Ae	80.53%	96.36%
Combined Ana-Ae-UV	82.84%	99.98%

Table E.9. TOC and TN values from the UV/H_2O_2 process alone for the calculation of the optimal H_2O_2 dosage.

Optimum H_2O_2 Dosage in the UV/ H_2O_2 process										V sln (mL)	1400
Slaughterhouse WW (%)		**5**	V sww (mL)	70		HRT (min)					
H_2O_2 Dosage (mg/L)			Parameter (mg/L)	dw	0	30	60	90	120	150	180
0	m H_2O_2 (mg)	0	TOC	0.9888	64.8812	64.498	63.8797	63.6042	62.246	60.7551	60.3673
	V Distilled Water (mL)	1330	SD	0.0788	3.5568	3.606	5.633	3.0488	3.0731	3.8387	0.7003
			TOC/TOC_0		1.0000	0.9941	0.9846	0.9803	0.9594	0.9364	0.9304
			TOC removal (%)	0.00%	0.00%	0.59%	1.54%	1.97%	4.06%	6.36%	6.96%
			TN	0.0366	19.8650	19.6	19.555	19.514	19.485	19.437	19.241
			SD	0.0015	1.3592	1.5718	1.9075	1.8673	2.1294	1.0639	1.9316
			TN/TN_0		1.0000	0.9867	0.9844	0.9823	0.9809	0.9785	0.9686
			TN Change (%)	0.00%	0.00%	1.33%	1.56%	1.77%	1.91%	2.15%	3.14%
			$[H_2O_2]/[TOC]$			0.00					
			$[H_2O_2]/(TOCinxHRT)$			0.00	0.00	0.00	0.00	0.00	0.00
100	m H_2O_2 (mg)	140	TOC	1.0485	64.8836	60.4931	58.3678	55.8508	52.3548	49.2112	39.8427
	V Distilled Water (mL)	1330	SD	0.0459	3.4583	2.7741	2.8606	2.0636	2.2383	2.2893	2.2795
			TOC/TOC_0		1.0000	0.9323	0.8996	0.8608	0.8069	0.7585	0.6141
			TOC removal (%)	0.00%	0.00%	6.77%	10.04%	13.92%	19.31%	24.15%	38.59%
			TN	0.0297	18.6996	18.5401	18.4696	18.326	18.2679	18.2777	17.6063
			SD	0.0035	1.0841	1.1699	1.3469	0.9926	1.2757	1.2993	1.1777
			TN/TN_0		1.0000	0.9915	0.9877	0.9800	0.9769	0.9774	0.9415
			TN Change (%)	0.00%	0.00%	0.85%	1.23%	2.00%	2.31%	2.26%	5.85%
			$[H_2O_2]/[TOC]$			1.54					
			$[H_2O_2]/(TOCinxHRT)$			3.08	1.54	1.03	0.77	0.62	0.51
300	m H_2O_2 (mg)	420	TOC	1.3880	64.8812	39.3727	38.9027	34.3628	28.5654	28.347	28.2534
	V Distilled Water (mL)	1330	SD	0.0692	3.7933	2.1217	1.0307	1.2012	1.1001	1.0173	0.9802
			TOC/TOC_0		1.0000	0.6068	0.5996	0.5296	0.4403	0.4369	0.4355
			TOC removal (%)	0.00%	0.00%	39.32%	40.04%	47.04%	55.97%	56.31%	56.45%
			TN	0.0148	16.5127	16.4987	16.4012	16.2228	16.1846	16.1207	15.9192
			SD	0.0143	1.4751	1.2457	0.7738	0.8801	1.3639	1.0672	0.993
			TN/TN_0		1.0000	0.9992	0.9932	0.9824	0.9801	0.9763	0.9641
			TN Change (%)	0.00%	0.00%	0.08%	0.68%	1.76%	1.99%	2.37%	3.59%
			$[H_2O_2]/[TOC]$			4.62					
			$[H_2O_2]/(TOCinxHRT)$			9.25	4.62	3.08	2.31	1.85	1.54
600	m H_2O_2 (mg)	840	TOC	0.6470	64.8842	38.5881	37.8008	33.9849	28.4601	23.8511	18.898
	V Distilled Water (mL)	1330	SD	0.1398	3.0402	0.9236	1.6197	1.477	1.3188	1.5034	0.9936
			TOC/TOC_0		1.0000	0.5947	0.5826	0.5238	0.4386	0.3676	0.2913
			TOC removal (%)	0.00%	0.00%	40.53%	41.74%	47.62%	56.14%	63.24%	70.87%
			TN	0.0250	20.6174	20.5333	20.5276	20.4338	19.9723	19.8345	19.7215

Optimum H_2O_2 Dosage in the UV/ H_2O_2 process										V sln (mL)	1400
Slaughterhouse WW (%)		**5**	V sww (mL)	70		HRT (min)					
H_2O_2 Dosage (mg/L)			Parameter (mg/L)	dw	0	30	60	90	120	150	180
			SD	0.0059	1.8660	0.9053	1.2178	1.6005	1.0582	1.4121	1.5613
			TN/TN_0		1.0000	0.9959	0.9956	0.9911	0.9687	0.9620	0.9565
			TN Change (%)	0.00%	0.00%	0.41%	0.44%	0.89%	3.13%	3.80%	4.35%
			$[H_2O_2]/[TOC]$			9.25					
			$[H_2O_2]/(TOCinxHRT)$			18.49	9.25	6.16	4.62	3.70	3.08
900	m H_2O_2 (mg)	1260	TOC	0.3740	64.8819	36.7201	22.8092	20.4505	19.7382	17.643	16.0794
	V Distilled Water (mL)	1330	SD	0.0930	2.7177	1.0475	0.9981	0.7622	0.6392	0.8176	0.5407
			TOC/TOC_0		1.0000	0.5660	0.3515	0.3152	0.3042	0.2719	0.2478
			TOC removal (%)	0.00%	0.00%	43.40%	64.85%	68.48%	69.58%	72.81%	75.22%
			TN	0.0021	16.9463	16.8832	16.7927	16.6849	16.5805	16.4137	16.3934
			SD	0.0113	1.2114	1.4301	1.1453	1.1435	1.0645	1.3149	0.8095
			TN/TN_0		1.0000	0.9963	0.9909	0.9846	0.9784	0.9686	0.9674
			TN Change (%)	0.00%	0.00%	0.37%	0.91%	1.54%	2.16%	3.14%	3.26%
			$[H_2O_2]/[TOC]$			13.87					
			$[H_2O_2]/(TOCinxHRT)$			27.74	13.87	9.25	6.94	5.55	4.62
1200	m H_2O_2 (mg)	1680	TOC	0.3438	64.8838	42.6663	30.2953	25.4318	24.1616	23.6652	19.7739
	V Distilled Water (mL)	1330	SD	0.0425	0.1557	0.8775	0.7127	0.715	0.4969	3.6254	0.9587
			TOC/TOC_0		1.0000	0.6576	0.4669	0.3920	0.3724	0.3647	0.3048
			TOC removal (%)	0.00%	0.00%	34.24%	53.31%	60.80%	62.76%	63.53%	69.52%
			TN	0.0124	19.8745	19.867	19.7409	19.6798	19.5703	19.41	18.981
			SD	0.0065	2.0548	1.1183	1.2375	1.0352	1.4666	1.1897	1.6439
			TN/TN_0		1.0000	0.9996	0.9933	0.9902	0.9847	0.9766	0.9550
			TN Change (%)	0.00%	0.00%	0.04%	0.67%	0.98%	1.53%	2.34%	4.50%
			$[H_2O_2]/[TOC]$			18.49					
			$[H_2O_2]/(TOCinxHRT)$			36.99	18.49	12.33	9.25	7.40	6.16
1500	m H_2O_2 (mg)	2100	TOC	0.3718	64.8830	63.9984	50.3561	35.6972	34.5233	34.1731	25.0047
	V Distilled Water (mL)	1330	SD	0.0530	6.5094	0.8207	1.6583	0.3918	1.3465	1.8898	0.2147
			TOC/TOC_0		1.0000	0.9864	0.7761	0.5502	0.5321	0.5267	0.3854
			TOC removal (%)	0.00%	0.00%	1.36%	22.39%	44.98%	46.79%	47.33%	61.46%
			TN	0.0556	10.3963	10.3867	10.283	10.1689	10.0935	10.0381	9.9416
			SD	0.0117	0.4491	1.1183	0.3182	0.3403	0.5518	0.3106	0.292
			TN/TN_0		1.0000	0.9991	0.9891	0.9781	0.9709	0.9655	0.9563
			TN Change (%)	0.00%	0.00%	0.09%	1.09%	2.19%	2.91%	3.45%	4.37%
			$[H_2O_2]/[TOC]$			23.12					
			$[H_2O_2]/(TOCinxHRT)$			46.24	23.12	15.41	11.56	9.25	7.71
2000	m H_2O_2 (mg)	2800	TOC	0.4726	64.8841	63.897	45.5644	42.8875	41.9274	41.2667	40.8396
	V Distilled Water (mL)	1330	SD	0.1458	2.9642	1.6737	0.9256	1.1876	2.2823	0.9188	1.5858

Optimum H_2O_2 Dosage in the UV/ H_2O_2 process										V sln (mL)	1400
Slaughterhouse WW (%)		**5**	V sww (mL)	70		HRT (min)					
H_2O_2 Dosage (mg/L)			Parameter (mg/L)	dw	0	30	60	90	120	150	180
			TOC/TOC_0		1.0000	0.9848	0.7022	0.6610	0.6462	0.6360	0.6294
			TOC removal (%)	0.00%	0.00%	1.52%	29.78%	33.90%	35.38%	36.40%	37.06%
			TN	0.0155	22.2402	21.9235	21.8382	21.7625	21.5683	21.3475	21.2496
			SD	0.0019	1.4422	1.3388	0.9942	1.3951	2.5865	1.4755	2.3422
			TN/TN_0		1.0000	0.9858	0.9819	0.9785	0.9698	0.9599	0.9555
			TN Change (%)	0.00%	0.00%	1.42%	1.81%	2.15%	3.02%	4.01%	4.45%
			$[H_2O_2]/[TOC]$			30.82					
			$[H_2O_2]/(TOCinxHRT)$			61.65	30.82	20.55	15.41	12.33	10.27

Optimum H_2O_2 Dosage in the UV/H_2O_2 process										V sln (mL)	1400
Slaughterhouse WW (%)		**10**	V sww (mL)	140		HRT (min)					
H_2O_2 Dosage (mg/L)			Parameter (mg/L)	dw	Inlet	30	60	90	120	150	180
0	m H_2O_2 (mg)	0	TOC	0.0122	163.6900	160.2435	156.213	155.5179	154.5622	153.2718	153.1581
	V Distilled Water (mL)	1260	SD	0.0263	2.3712	2.404	3.7553	2.032	2.0487	2.5591	0.4668
			TOC/TOC_0		1.0000	0.9789	0.9543	0.9501	0.9442	0.9364	0.9357
			TOC removal (%)	0.00%	0.00%	2.11%	4.57%	4.99%	5.58%	6.36%	6.43%
	163.69		TN	0.1212	10.2823	10.233	10.217	10.1722	10.0427	9.9681	9.8264
			SD	0.0095	0.4446	0.5367	0.315	0.3369	0.3075	0.2384	0.3005
			TN/TN_0		1.0000	0.9952	0.9936	0.9893	0.9767	0.9694	0.9557
			TN Change (%)	0.00%	0.00%	0.48%	0.64%	1.07%	2.33%	3.06%	4.43%
			$[H_2O_2]/[TOC]$			0.00					
			$[H_2O_2]/(TOCinxHRT)$			0.00	0.00	0.00	0.00	0.00	0.00
100	m H_2O_2 (mg)	140	TOC	0.4435	163.6918	158.6074	155.5373	151.9234	145.709	142.1115	135.4624
	V Distilled Water (mL)	1260	SD	0.0874	1.1920	1.6798	5.1214	4.6248	1.972	5.6382	3.6488
			TOC/TOC_0		1.0000	0.9689	0.9502	0.9281	0.8901	0.8682	0.8275
			TOC removal (%)	0.00%	0.00%	3.11%	4.98%	7.19%	10.99%	13.18%	17.25%
			TN	0.1231	10.3963	10.3495	10.33	10.2689	10.1381	10.0627	9.9319
			SD	0.0096	0.4491	0.5422	0.3182	0.3403	0.3106	0.2409	0.3035
			TN/TN_0		1.0000	0.9955	0.9936	0.9877	0.9752	0.9679	0.9553
			TN Change (%)	0.00%	0.00%	0.45%	0.64%	1.23%	2.48%	3.21%	4.47%
			$[H_2O_2]/[TOC]$			0.61					
			$[H_2O_2]/(TOCinxHRT)$			1.22	0.61	0.41	0.31	0.24	0.20
300	m H_2O_2 (mg)	420	TOC	0.4024	163.6924	148.8065	133.7997	127.6608	117.3482	109.9497	107.424
	V Distilled Water (mL)	1260	SD	0.0439	5.2009	6.4821	2.4589	4.7017	8.2834	1.9445	5.792
			TOC/TOC_0		1.0000	0.9091	0.8174	0.7799	0.7169	0.6717	0.6563
			TOC removal (%)	0.00%	0.00%	9.09%	18.26%	22.01%	28.31%	32.83%	34.37%
			TN	0.0374	35.1243	34.4741	34.3737	34.0614	33.7346	33.5985	33.5482

Optimum H_2O_2 Dosage in the UV/H_2O_2 process										V sln (mL)	1400
Slaughterhouse WW (%)		**10**	V sww (mL)	140		HRT (min)					
H_2O_2 Dosage (mg/L)			Parameter (mg/L)	dw	Inlet	30	60	90	120	150	180
			SD	0.0114	3.7716	3.008	2.6123	2.9253	4.5748	1.4837	3.656
			TN/TN_0		1.0000	0.9815	0.9786	0.9697	0.9604	0.9566	0.9551
			TN Change (%)	0.00%	0.00%	1.85%	2.14%	3.03%	3.96%	4.34%	4.49%
			$[H_2O_2]/[TOC]$			1.83					
			$[H_2O_2]/(TOCinxHRT)$			3.67	1.83	1.22	0.92	0.73	0.61
600	m H_2O_2 (mg)	840	TOC	1.2403	163.6931	136.7233	121.2595	111.0704	102.4181	95.0924	82.7712
	V Distilled Water (mL)	1260	SD	0.0691	8.6615	11.9802	7.254	5.1248	0.3397	3.8398	4.3951
			TOC/TOC_0		1.0000	0.8352	0.7408	0.6785	0.6257	0.5809	0.5056
			TOC removal (%)	0.00%	0.00%	16.48%	25.92%	32.15%	37.43%	41.91%	49.44%
			TN	0.2023	36.2005	36.0021	35.8837	35.56	35.427	35.1153	34.7423
			SD	0.0201	4.8040	3.2864	1.9203	3.0515	2.6251	2.7583	2.3554
			TN/TN_0		1.0000	0.9945	0.9912	0.9823	0.9786	0.9700	0.9597
			TN Change (%)	0.00%	0.00%	0.55%	0.88%	1.77%	2.14%	3.00%	4.03%
			$[H_2O_2]/[TOC]$			3.67					
			$[H_2O_2]/(TOCinxHRT)$			7.33	3.67	2.44	1.83	1.47	1.22
900	m H_2O_2 (mg)	1260	TOC	0.3937	163.6918	146.0666	127.4692	113.1575	97.5334	84.8794	73.5083
	V Distilled Water (mL)	1260	SD	0.0481	7.4853	6.2527	3.3747	6.588	1.6574	0.7566	0.2433
			TOC/TOC_0		1.0000	0.8923	0.7787	0.6913	0.5958	0.5185	0.4491
			TOC removal (%)	0.00%	0.00%	10.77%	22.13%	30.87%	40.42%	48.15%	55.09%
			TN	0.0204	36.2292	36.0641	35.653	35.48	35.42	34.8381	34.7872
			SD	0.0037	3.2827	2.862	2.1929	3.3961	1.7362	2.6891	2.6898
			TN/TN_0		1.0000	0.9954	0.9841	0.9793	0.9777	0.9616	0.9602
			TN Change (%)	0.00%	0.00%	0.46%	1.59%	2.07%	2.23%	3.84%	3.98%
			$[H_2O_2]/[TOC]$			5.50					
			$[H_2O_2]/(TOCinxHRT)$			11.00	5.50	3.67	2.75	2.20	1.83
1200	m H_2O_2 (mg)	1680	TOC	0.3649	163.6946	138.4621	128.2274	113.4087	103.2957	89.8321	78.6498
	V Distilled Water (mL)	1260	SD	0.0530	4.7491	5.3629	3.0035	2.952	2.4297	0.9795	0.2433
			TOC/TOC_0		1.0000	0.8459	0.7833	0.6928	0.6310	0.5488	0.4805
			TOC removal (%)	0.00%	0.00%	15.41%	21.67%	30.72%	36.90%	45.12%	51.95%
			TN	0.0388	42.9504	42.9383	42.5951	41.8654	40.9288	40.9206	40.7872
			SD	0.0049	3.3682	3.5499	3.5455	2.7798	3.2706	1.8759	2.6898
			TN/TN_0		1.0000	0.9997	0.9917	0.9747	0.9529	0.9527	0.9496
			TN Change (%)	0.00%	0.00%	0.03%	0.83%	2.53%	4.71%	4.73%	5.04%
			$[H_2O_2]/[TOC]$			7.33					
			$[H_2O_2]/(TOCinxHRT)$			14.66	7.33	4.89	3.67	2.93	2.44
1500	m H_2O_2 (mg)	2100	TOC	0.3199	163.6949	145.7094	141.309	128.7489	117.4279	109.9103	98.9008
	V Distilled Water (mL)	1260	SD	0.1460	4.2571	2.407	0.7325	0.3592	3.6086	2.6835	2.4337

Optimum H_2O_2 Dosage in the UV/H_2O_2 process										V sln (mL)	1400
Slaughterhouse WW (%)		**10**	V sww (mL)	140		HRT (min)					
H_2O_2 Dosage (mg/L)			Parameter (mg/L)	dw	Inlet	30	60	90	120	150	180
			TOC/TOC_0		1.0000	0.8901	0.8632	0.7865	0.7174	0.6714	0.6042
			TOC removal (%)	0.00%	0.00%	10.99%	13.68%	21.35%	28.26%	32.86%	39.58%
			TN	0.0059	39.2642	38.0812	37.9143	37.7673	37.6885	37.5354	37.4503
			SD	0.0239	1.1824	2.01	1.431	0.9946	3.6654	4.0569	4.4301
			TN/TN_0		1.0000	0.9699	0.9656	0.9619	0.9599	0.9560	0.9538
			TN Change (%)	0.00%	0.00%	3.01%	3.44%	3.81%	4.01%	4.40%	4.62%
			[H_2O_2]/[TOC]			9.16					
			[H_2O_2]/(TOCinxHRT)			18.33	9.16	6.11	4.58	3.67	3.05
2000	m H_2O_2 (mg)	2800	TOC	0.4015	163.6923	158.7729	155.0396	154.1321	140.52508	136.9603	136.799
	V Distilled Water (mL)	1260	SD	0.2849	4.2162	2.943	2.84	3.9541	3.2802	2.0163	2.9217
			TOC/TOC_0		1.0000	0.9699	0.9471	0.9416	0.8585	0.8367	0.8357
			TOC removal (%)	0.00%	0.00%	3.01%	5.29%	5.84%	14.15%	16.33%	16.43%
			TN	0.0102	40.0242	39.7212	39.5277	39.356	38.8934	38.5018	38.2116
			SD	0.0015	0.2588	0.1871	0.2875	0.2021	1.2633	1.3846	0.4478
			TN/TN_0		1.0000	0.9924	0.9876	0.9833	0.9717	0.9620	0.9547
			TN Change (%)	0.00%	0.00%	0.76%	1.24%	1.67%	2.83%	3.80%	4.53%
			[H_2O_2]/[TOC]			12.22					
			[H_2O_2]/(TOCinxHRT)			24.44	12.22	8.15	6.11	4.89	4.07

Optimum H_2O_2 Dosage in the UV/H_2O_2 process										V sln (mL)	1400
Slaughterhouse WW (%)		**25**	V sww (mL)	350		HRT (min)					
H_2O_2 Dosage (mg/L)			Parameter (mg/L)	dw	Inlet	30	60	90	120	150	180
0	m H_2O_2 (mg)	0	TOC	1.6557	349.8443	349.5167	346.8376	341.9938	336.522	335.4213	333.9472
	V Distilled Water (mL)	1050	SD	0.4234	13.9950	12.62	13.252	6.6848	8.9175	8.8915	16.649
			TOC/TOC_0		1.0000	0.9991	0.9914	0.9776	0.9619	0.9588	0.9546
			TOC removal (%)	0.00%	0.00%	0.09%	0.86%	2.24%	3.81%	4.12%	4.54%
			TN	0.0543	61.6381	61.5705	61.1039	60.7614	60.4364	60.0095	59.7008
			SD	0.0432	4.0668	1.9383	4.8265	2.2845	4.4559	6.3232	5.0482
			TN/TN_0		1.0000	0.9989	0.9913	0.9858	0.9805	0.9736	0.9686
			TN Change (%)	0.00%	0.00%	0.11%	0.87%	1.42%	1.95%	2.64%	3.14%
			[H_2O_2]/[TOC]			0.00					
			[H_2O_2]/(TOCinxHRT)			0.00	0.00	0.00	0.00	0.00	0.00
100	m H_2O_2 (mg)	140	TOC	4.2884	349.8411	348.4553	346.4201	342.7185	337.8742	336.1836	327.7204
	V Distilled Water (mL)	1050	SD	2.9827	17.6220	16.904	20.258	12.451	18.429	15.021	17.494
			TOC/TOC_0		1.0000	0.9960	0.9902	0.9796	0.9658	0.9610	0.9368
			TOC removal (%)	0.00%	0.00%	0.40%	0.98%	2.04%	3.42%	3.90%	6.32%
			TN	0.0497	74.3675	73.1756	72.5167	71.1686	70.6972	70.6734	70.0148

Optimum H_2O_2 Dosage in the UV/H_2O_2 process										V sln (mL)	1400
Slaughterhouse WW (%)		**25**	V sww (mL)	350		HRT (min)					
H_2O_2 Dosage (mg/L)			Parameter (mg/L)	dw	Inlet	30	60	90	120	150	180
			SD	0.0012	1.5100	5.2891	5.0212	3.3433	0.9933	8.5419	4.5883
			TN/TN_0		1.0000	0.9840	0.9751	0.9570	0.9506	0.9503	0.9415
			TN Change (%)	0.00%	0.00%	1.60%	2.49%	4.30%	4.94%	4.97%	5.85%
			$[H_2O_2]/[TOC]$			0.29					
			$[H_2O_2]/(TOCinxHRT)$			0.57	0.29	0.19	0.14	0.11	0.10
300	m H_2O_2 (mg)	420	TOC	1.6431	349.8427	336.4419	333.3634	330.9912	325.8514	316.1888	315.0332
	V Distilled Water (mL)	1050	SD	0.0559	17.9241	26.172	23.4321	0.4875	19.4917	13.6321	13.4115
			TOC/TOC_0		1.0000	0.9617	0.9529	0.9461	0.9314	0.9038	0.9005
			TOC removal (%)	0.00%	0.00%	3.83%	4.71%	5.39%	6.86%	9.62%	9.95%
			TN	0.0306	72.6251	72.3155	72.2175	70.6664	69.9098	69.0482	68.2953
			SD	0.0027	5.0380	5.5156	7.5996	4.8989	4.5144	5.6787	5.1128
			TN/TN_0		1.0000	0.9957	0.9944	0.9730	0.9626	0.9507	0.9404
			TN Change (%)	0.00%	0.00%	0.43%	0.56%	2.70%	3.74%	4.93%	5.96%
			$[H_2O_2]/[TOC]$			0.86					
			$[H_2O_2]/(TOCinxHRT)$			1.72	0.86	0.57	0.43	0.34	0.29
600	m H_2O_2 (mg)	840	TOC	0.3863	349.8389	348.7115	332.358	312.272	306.8418	302.2664	298.1659
	V Distilled Water (mL)	1050	SD	0.0274	2.6704	19792	2.1623	3.2609	2.4531	2.6767	0.3585
			TOC/TOC_0		1.0000	0.9968	0.9500	0.8926	0.8771	0.8640	0.8523
			TOC removal (%)	0.00%	0.00%	0.32%	5.00%	10.74%	12.29%	13.60%	14.77%
			TN	0.0083	113.4200	112.914	111.27	110.334	108.319	107.898	107.275
			SD	0.0085	4.0811	0.8786	1.2365	1.256	1.4943	1.2049	0.4066
			TN/TN_0		1.0000	0.9955	0.9810	0.9728	0.9550	0.9513	0.9458
			TN Change (%)	0.00%	0.00%	0.45%	1.90%	2.72%	4.50%	4.87%	5.42%
			$[H_2O_2]/[TOC]$			1.72					
			$[H_2O_2]/(TOCinxHRT)$			3.43	1.72	1.14	0.86	0.69	0.57
900	m H_2O_2 (mg)	1260	TOC	0.3469	349.8393	346.8428	343.778	336.9154	326.933	301.613	283.3343
	V Distilled Water (mL)	1050	SD	0.0681	3.7327	2.022	2.2931	1.7084	2.6565	1.8778	1.7784
			TOC/TOC_0		1.0000	0.9914	0.9827	0.9631	0.9345	0.8621	0.8099
			TOC removal (%)	0.00%	0.00%	0.86%	1.73%	3.69%	6.55%	13.79%	19.01%
			TN	0.0110	111.4290	110.128	108.166	107.759	106.646	105.98	104.7991
			SD	0.0027	0.9575	1.0278	0.9873	0.6779	0.7238	1.0256	0.6821
			TN/TN_0		1.0000	0.9883	0.9707	0.9671	0.9571	0.9511	0.9405
			TN Change (%)	0.00%	0.00%	1.17%	2.93%	3.29%	4.29%	4.89%	5.95%
			$[H_2O_2]/[TOC]$			2.57					
			$[H_2O_2]/(TOCinxHRT)$			5.15	2.57	1.72	1.29	1.03	0.86
1200	m H_2O_2 (mg)	1680	TOC	1.2265	349.8442	345.2325	342.5441	331.5783	324.9635	318.5033	267.616
	V Distilled Water (mL)	1050	SD	0.0886	9.5327	1.948	2.2193	4.6672	4.2282	3.6242	2.5053

Optimum H_2O_2 Dosage in the UV/H_2O_2 process										V sln (mL)	1400
Slaughterhouse WW (%)		**25**	V sww (mL)	350		HRT (min)					
H_2O_2 Dosage (mg/L)			Parameter (mg/L)	dw	Inlet	30	60	90	120	150	180
			TOC/TOC_0		1.0000	0.9868	0.9791	0.9478	0.9289	0.9104	0.7650
			TOC removal (%)	0.00%	0.00%	1.32%	2.09%	5.22%	7.11%	8.96%	23.50%
			TN	0.0856	107.9430	106.9074	106.4394	105.4304	104.1949	103.4741	102.9584
			SD	0.0025	2.0639	1.4994	2.213	3.2364	2.6889	3.4585	2.1362
			TN/TN_0		1.0000	0.9904	0.9861	0.9767	0.9653	0.9586	0.9538
			TN Change (%)	0.00%	0.00%	0.96%	1.39%	2.33%	3.47%	4.14%	4.62%
			[H_2O_2]/[TOC]			3.43					
			[H_2O_2]/(TOCinxHRT)			6.86	3.43	2.29	1.72	1.37	1.14
1500	m H_2O_2 (mg)	2100	TOC	0.2490	349.8422	347.4996	346.0875	344.9723	341.9518	330.7287	290.0434
	V Distilled Water (mL)	1050	SD	0.0055	1.1366	6.0903	5.8592	2.3846	0.5781	1.616	3.9513
			TOC/TOC_0		1.0000	0.9933	0.9893	0.9861	0.9774	0.9454	0.8291
			TOC removal (%)	0.00%	0.00%	0.67%	1.07%	1.39%	2.26%	5.46%	17.09%
			TN	0.0230	98.6301	97.7744	96.4157	95.1634	94.0978	93.818	92.7965
			SD	0.0007	2.4716	2.9493	1.7532	1.2818	1.6925	1.6997	3.1472
			TN/TN_0		1.0000	0.9913	0.9775	0.9649	0.9540	0.9512	0.9409
			TN Change (%)	0.00%	0.00%	0.87%	2.25%	3.51%	4.60%	4.88%	5.91%
			[H_2O_2]/[TOC]			4.29					
			[H_2O_2]/(TOCinxHRT)			8.58	4.29	2.86	2.14	1.72	1.43
2000	m H_2O_2 (mg)	2800	TOC	0.2279	349.8415	346.5791	343.3765	341.8818	340.99	335.1191	330.0051
	V Distilled Water (mL)	1050	SD	0.0352	5.7086	3.3289	6.2872	6.1553	5.6319	1.6076	4.5845
			TOC/TOC_0		1.0000	0.9907	0.9815	0.9772	0.9747	0.9579	0.9433
			TOC removal (%)	0.00%	0.00%	0.93%	1.85%	2.28%	2.53%	4.21%	5.67%
			TN	0.0135	93.9385	93.1295	92.05225	91.29675	90.401	89.468	88.3123
			SD	0.0033	1.8904	1.6859	2.6718	2.1883	2.6227	2.2951	3.3716
			TN/TN_0		1.0000	0.9914	0.9799	0.9719	0.9623	0.9524	0.9401
			TN Change (%)	0.00%	0.00%	0.86%	2.01%	2.81%	3.77%	4.76%	5.99%
			[H_2O_2]/[TOC]			5.72					
			[H_2O_2]/(TOCinxHRT)			11.43	5.72	3.81	2.86	2.29	1.91

Table E.10. Kinetic modeling for the different processes.

ABR process alone modeling

S_0	1008.8495	mg/L	S_1	578.6266	mg/L	S_2	420.5742	mg/L	S_3	332.9334	mg/L	S_4	270.5846	mg/L
S_1	578.6266	mg/L	S_2	420.5742	mg/L	S_3	332.9334	mg/L	S_4	270.5846	mg/L	S_5	106.2775	mg/L
X_1	13325	mg/L	X_2	11550	mg/L	X_3	16150	mg/L	X_4	10600	mg/L	X_5	11833	mg/L
V_1	6.74	L	V_2	6.74	L	V_3	6.74	L	V_4	6.74	L	V_5	6.74	L
t	7	d	t	7	d	t	7	d	t	7	d	t	7	d
V	33.7	L	V	33.7	L	V	33.7	L	V	33.7	L	V	33.7	L
k_{C1}	3.9857E-05		k_{C2}	2.3241E-05		k_{C3}	1.1643E-05		k_{C4}	1.5527E-05		k_{C5}	9.3321E-05	
8.98E+04	0.1062		7.78E+04	0.0537		1.09E+05	0.0376		7.14E+04	0.0329		7.98E+04	0.2209	
S_{1m}	578.6266		S_{2m}	420.5742		S_{3m}	332.9334		S_{4m}	270.5846		S_{5m}	106.2775	

ABR Process Alone

HRT (d)	S_0 (mg/L)	S_f Experiments (mg/L)	S_f Model (mg/L)	% TOC $_{removal}$ Experiments	% TOC $_{removal}$ Model	Error
2	733.42	312.98	330.62	57.33%	54.92%	0.06%
3	1008.85	208.73	324.14	79.31%	67.87%	1.31%
5	639.44	104.61	113.09	83.64%	82.31%	0.02%
5	733.42	129.97	129.71	82.28%	82.31%	0.00%
7	1008.85	106.28	106.28	89.47%	89.47%	0.00%
7	183.35	29.24	19.32	84.06%	89.47%	0.29%
7	366.71	57.85	38.63	84.23%	89.47%	0.27%
7	639.44	80.45	67.36	87.42%	89.47%	0.04%
7	733.42	88.43	77.26	87.94%	89.47%	0.02%
8	639.44	71.09	53.18	88.88%	91.68%	0.08%
					Σ Error	2.10%

Aerobic AS process alone modeling

S_0	1008.8495	mg/L
S_f	55.2232	mg/L
X	2399	mg/L
t	7	d
K	1.0283E-03	
	2.4669	

Aerobic AS Process Alone

HRT (d)	S_0 (mg/L)	S_f Experiments (mg/L)	S_f Model (mg/L)	% TOC $_{removal}$ Experiments	% TOC $_{removal}$ Model	Error
7	183.35	14.48	10.04	92.10%	94.53%	0.06%
7	366.71	28.19	20.07	92.31%	94.53%	0.05%
5	639.44	66.14	47.95	89.66%	92.50%	0.08%
7	639.44	46.94	35.00	92.66%	94.53%	0.03%
8	639.44	36.71	30.84	94.26%	95.18%	0.01%
2	733.42	143.00	123.60	80.50%	83.15%	0.07%
5	733.42	41.70	55.00	94.31%	92.50%	0.03%
7	733.42	40.78	40.15	94.44%	94.53%	0.00%
3	1008.85	84.08	120.09	91.67%	88.10%	0.13%
7	1008.85	55.22	55.22	94.53%	94.53%	0.00%
					Σ Error	0.46%

UV/H_2O_2 process alone modeling

p	14	W
ξ	6.8418E-09	mol/s.W
S_0	64.8819	mg/L
S_f	16.0794	mg/L
t	10800	s
V_T	1.35	L

H_2O_2	900	mg/L
S_f/S_o	0.2478	
K_{H2O2}	1	
K_{TOC}	112.6694556	
S_f/S_o model	0.177864833	
Error	5E-03	
S_f	11.54020831	
	7.9941E-06	

UV/H_2O_2 Process Alone

HRT (s)	S_0 (mg/L)	S_f Experiments (mg/L)	S_f Model (mg/L)	% TOC $_{removal}$ Experiments	% TOC $_{removal}$ Model	Error
1800	64.88	46.72	48.66	27.99%	25.01%	0.09%
3600	64.88	32.81	36.49	49.43%	43.76%	0.32%
5400	64.88	30.45	27.36	53.07%	57.83%	0.23%
7200	64.88	19.74	20.52	69.58%	68.37%	0.01%
9000	64.88	17.64	15.39	72.81%	76.28%	0.12%
10800	64.88	16.08	11.54	75.22%	82.21%	0.49%
					Σ Error	0.77%

Combined Anaerobic-Aerobic Processes modeling

S_0	1008.8495	mg/L	S_1	462.2498	mg/L	S_2	396.8390	mg/L	S_3	338.2224	mg/L	S_4	306.1535	mg/L	S_0	162.7555	mg/L
S_1	462.2498	mg/L	S_2	396.839	mg/L	S_3	338.2224	mg/L	S_4	306.1535	mg/L	S_5	162.7555	mg/L	S_f	36.6972	mg/L
X_1	13325	mg/L	X_2	11550	mg/L	X_3	16150	mg/L	X_4	10600	mg/L	X_5	11833	mg/L	X	2399	mg/L
V_1	6.74	L	V_2	6.74	L	V_3	6.74	L	V_4	6.74	L	V_5	6.74	L	t	6.24	d
t	6.24	d	t	6.24	d	t	6.24	d	t	6.24	d	t	6.24	d	K	2.29E-04	
V	45.7	L	V	45.7	L	V	45.7	L	V	45.7	L	V	45.7	L		0.5505	
k_{C1}	9.64E-05		k_{C2}	1.55E-05		k_{C3}	1.17E-05		k_{C4}	1.07E-05		k_{C5}	8.09E-05		S_{fm}	36.6972	
8.98E+04	0.1895		7.78E+04	0.0264		1.09E+05	0.0278		7.14E+04	0.0168		7.98E+04	0.1412		S_{1m}	36.6972	
S_{1m}	462.2498		S_{2m}	396.8390		S_{3m}	338.2224		S_{4m}	306.1535		S_{5m}	162.7555				
S_{1m}	462.2498		S_{1m}	396.8390		S_{1m}	338.2224		S_{1m}	306.1535		S_{1m}	162.7555				

Combined Anaerobic-Aerobic Processes

HRT (d)	S_0 (mg/L)	S_f Experiments (mg/L)	S_f Model (mg/L)	% TOC $_{removal}$ Experiments	% TOC $_{removal}$ Model	Error
3.12	1008.85	69.10	130.84	93.15%	87.03%	0.37%
6.24	1008.85	36.70	36.70	96.36%	96.36%	0.00%
4.68	1008.85	79.63	65.74	92.11%	93.48%	0.02%
9.36	1008.85	37.23	14.00	96.31%	98.61%	0.05%
2.08	1008.85	213.24	225.80	78.86%	77.62%	0.02%
					Σ Error	0.46%

Combined Aerobic-Anaerobic Processes modeling

S_0	1008.8495	mg/L	S_0	168.8271	mg/L	S_1	151.3520	mg/L	S_2	149.4387	mg/L	S_3	100.3359	mg/L	S_4	60.5536	mg/L
S_f	168.8271	mg/L	S_1	151.3520	mg/L	S_2	149.4387	mg/L	S_3	100.3359	mg/L	S_4	60.5536	mg/L	S_5	39.3044	mg/L
X	2399	mg/L	X_1	13325	mg/L	X_2	11550	mg/L	X_3	16150	mg/L	X_4	10600	mg/L	X_5	11833	mg/L
t	6.24	d	V_1	6.74	L	V_2	6.74	L	V_3	6.74	L	V_4	6.74	L	V_5	6.74	L
K	3.32E-04		t	6.24	d	t	6.24	d	t	6.24	d	t	6.24	d	t	6.24	d
	0.7974		V	45.7	L	V	45.7	L	V	45.7	L	V	45.7	L	V	45.7	L
			k_{C1}	9.42E-06		k_{C2}	1.20E-06		k_{C3}	3.29E-05		k_{C4}	6.73E-05		k_{C5}	4.96E-05	
			8.98E+04	0.0185		7.78E+04	0.0021		1.09E+05	0.0784		7.14E+04	0.1053		7.98E+04	0.0866	

S_{1m}	151.3520	S_{2m}	149.4387	S_{3m}	100.3359	S_{4m}	60.5536	S_{5m}	39.3044

Combined Aerobic-Anaerobic Processes

HRT (d)	S_0 (mg/L)	S_f Experiments (mg/L)	S_f Model (mg/L)	% TOC $_{removal}$ Experiments	% TOC $_{removal}$ Model	Error
3.12	1008.85	140.79	129.36	86.04%	87.18%	0.01%
6.24	1008.85	39.30	39.30	96.10%	96.10%	0.00%
4.68	1008.85	57.16	67.76	94.33%	93.28%	0.01%
9.36	1008.85	39.51	15.99	96.08%	98.42%	0.05%
2.08	1008.85	235.32	217.44	76.67%	78.45%	0.03%
					Σ Error	0.11%

Combined Anaerobic-Aerobic UV/H_2O_2 Processes modeling

S_0	1004.8855	mg/L	S_1	454.5485	mg/L	S_2	295.8308	mg/L	S_3	214.4315	mg/L	S_4	180.8297	mg/L	S_5	153.6721	mg/L	S_f	81.7164	mg/L	X	2399	mg/L
S_1	454.5485	mg/L	S_2	295.8308	mg/L	S_3	214.4315	mg/L	S_4	180.8297	mg/L	S_5	153.6721	mg/L	S_f	81.7164	mg/L	X	2399	mg/L	t	4.00	d
X_1	13325	mg/L	X_2	11550	mg/L	X_3	16150	mg/L	X_4	10600	mg/L	X_5	11833	mg/L	X	2399	mg/L	t	4.00	d	K	9.18E-05	
V_1	6.74	L	V_2	6.74	L	V_3	6.74	L	V_4	6.74	L	V_5	6.74	L	t	4.00	d	K	9.18E-05			0.2201	
t	4.00	d	t	4.00	d	t	4.00	d	t	4.00	d	t	4.00	d	K	9.18E-05			0.2201				
V	47.05	L	V	47.05	L	V	47.05	L	V	47.05	L	V	47.05	L		0.2201							
k_{C1}	1.59E-04		k_{C2}	8.11E-05		k_{C3}	4.10E-05		k_{C4}	3.06E-05		k_{C5}	2.61E-05										
8.98E+04	0.3027		7.78E+04	0.1341		1.09E+05	0.0949		7.14E+04	0.0465		7.98E+04	0.0442										
S_{1m}	454.5485		S_{2m}	295.8308		S_{3m}	214.4315		S_{4m}	180.8297		S_{5m}	153.6721										

p	14	W		
ξ	6.8418E-09	mol/s.W		
S_0	81.7164	mg/L	99.79%	
S_f	0.1682	mg/L		
t	4.00	d	5760	
V_T	47.05	L		
H_2O_2	900	mg/L	0.05	mol/L
S_f/S_o	0.0021			
K_{H2O2}	1			
K_{TOC}	1.34E+04			
S_f/S_o model	0.043121112	0.0393		
Error	2E-03			
S_f	81.53819506			
	2.7289E-05			

Combined Anaerobic-Aerobic UV/H_2O_2 Processes

HRT (d)	S_0 (mg/L)	S_f Experiments (mg/L)	S_f Model (mg/L)	% TOC $_{removal}$ Experiments	% TOC $_{removal}$ Model	Error
3.15	941.19	10.3053	9.9170	98.91%	98.95%	0.00%
3.50	1006.90	8.1433	6.7132	99.19%	99.33%	0.00%
4.00	1004.89	0.1682	3.5237	99.98%	99.65%	0.00%
7.00	1008.85	0.2234	0.0928	99.98%	99.99%	0.00%
2.50	1000.46	26.1234	25.1472	97.39%	97.49%	0.00%
					Σ Error	0.00%

Table E.11. Maximum TOC and TN removals using UV/H_2O_2 process alone.

	% TOC Removal			% TN Removal		
[H_2O_2] (mg/L)	SWW at 5%	SWW at 10%	SWW at 25%	SWW at 5%	SWW at 10%	SWW at 25%
0	6.96%	6.43%	4.54%	3.14%	4.43%	3.14%
100	38.59%	17.25%	6.32%	5.85%	4.47%	5.85%
300	56.45%	34.37%	9.95%	3.59%	4.49%	5.96%
600	70.87%	49.44%	14.77%	4.35%	4.03%	5.42%
900	75.22%	55.09%	19.01%	3.26%	3.98%	5.95%
1200	69.52%	51.95%	23.50%	4.50%	5.04%	4.62%
1500	61.46%	39.58%	17.09%	4.37%	4.62%	5.91%
2000	37.06%	16.43%	5.67%	4.45%	4.53%	5.99%

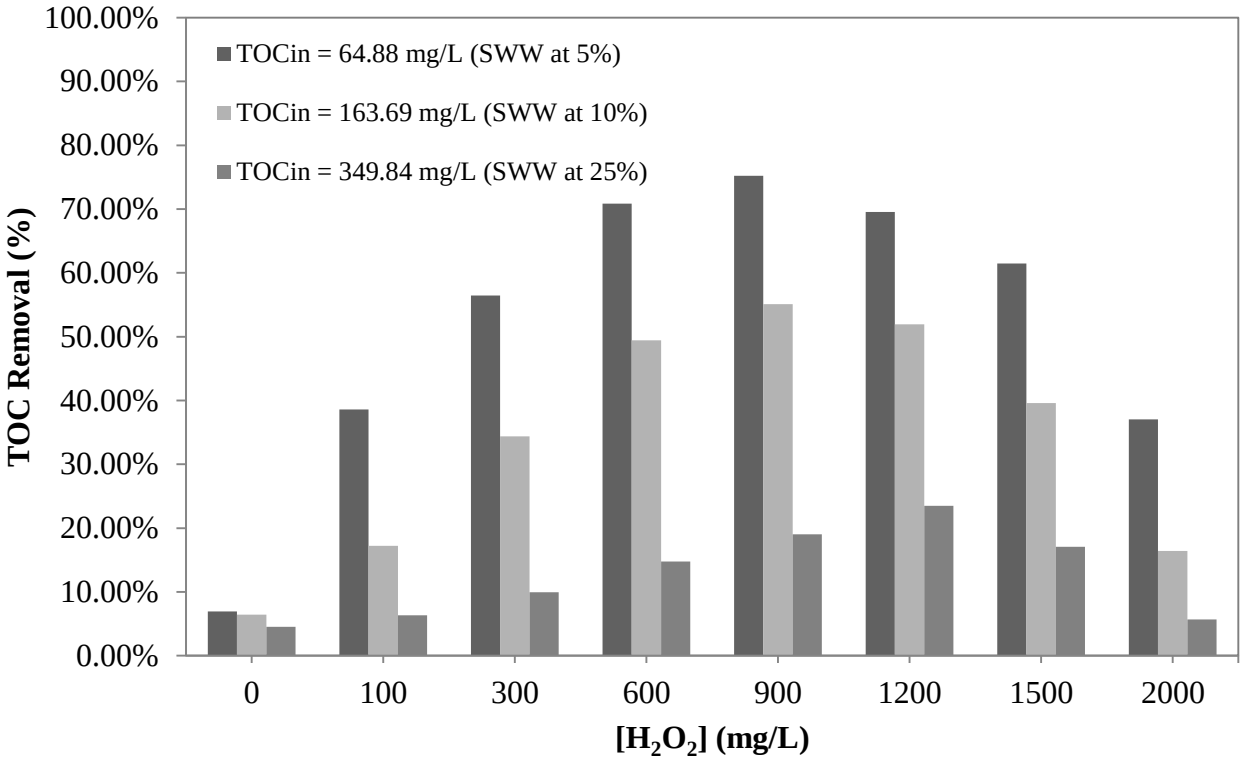


Figure E.1. Optimum TOC removal by using UV/H_2O_2 process alone.

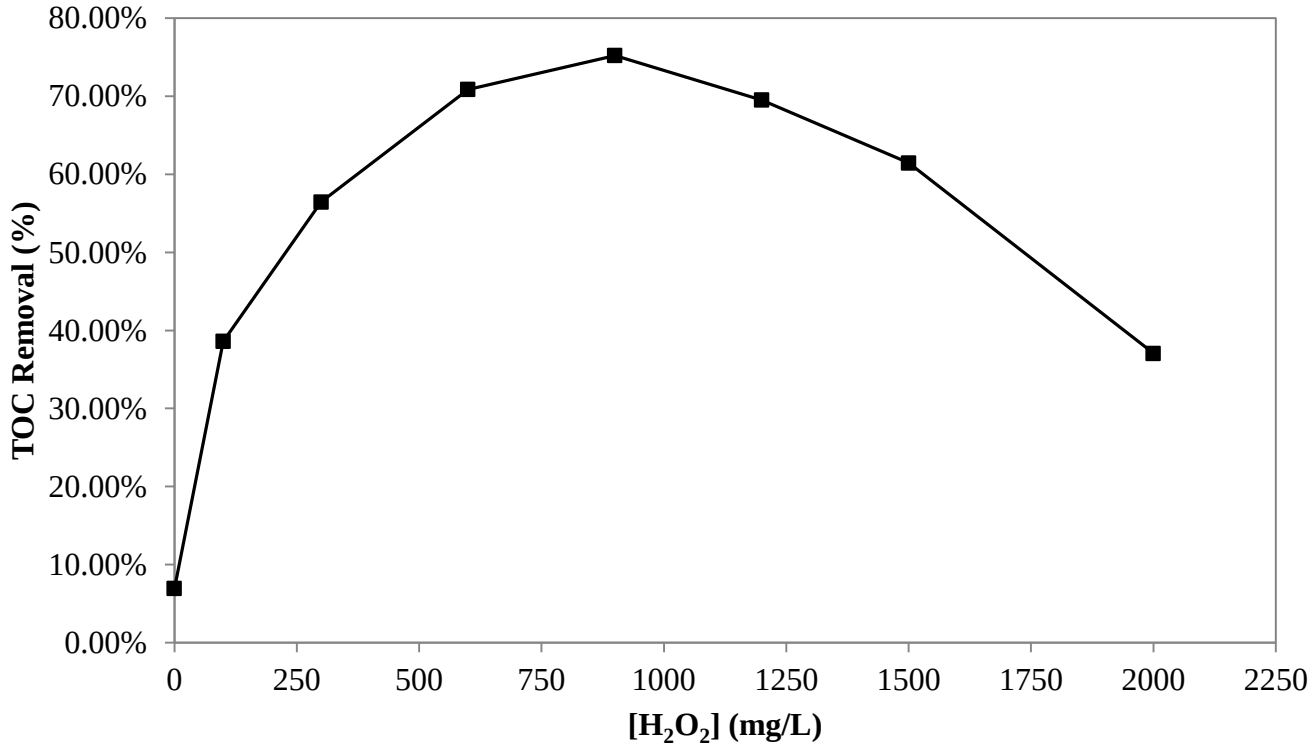


Figure E.2. Optimal Concentration of H_2O_2 for TOC removal of an influent concentration of 64.88mg/L.

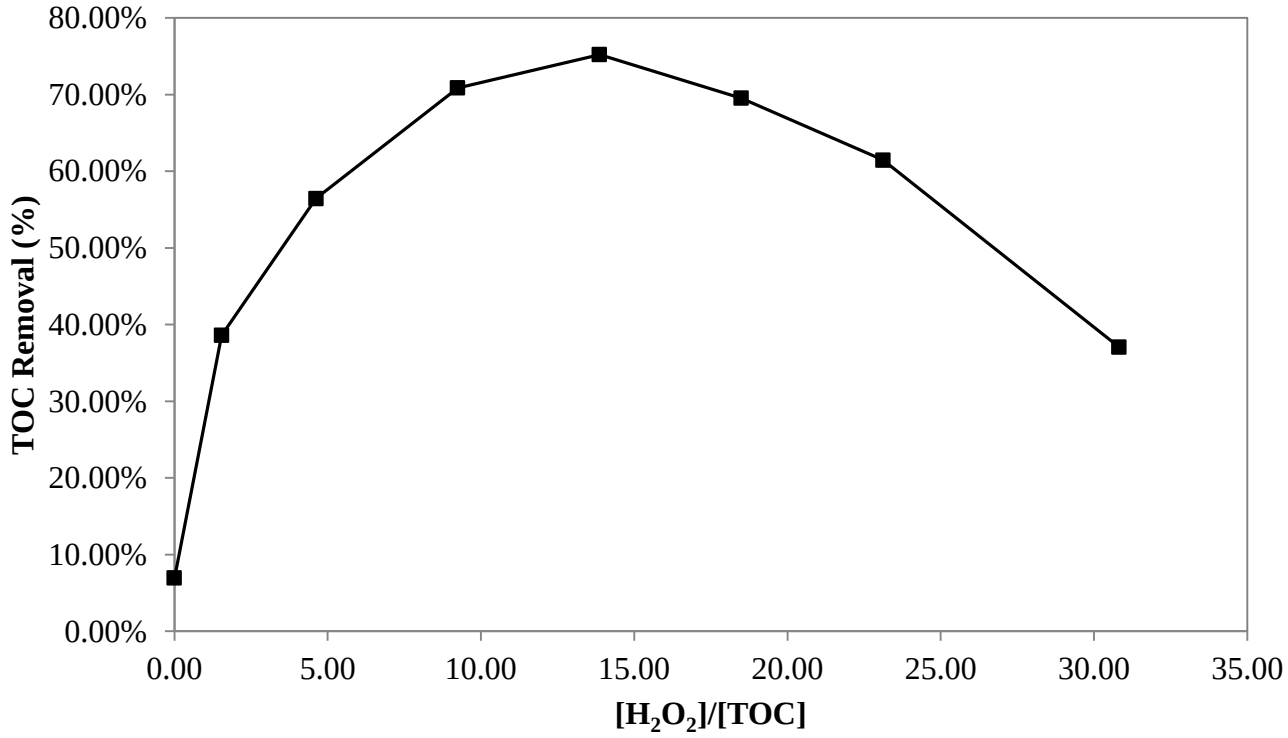


Figure E.3. Relation of molar ratio of $[H_2O_2]/[TOC]$ for an influent concentration of 64.88mg/L.

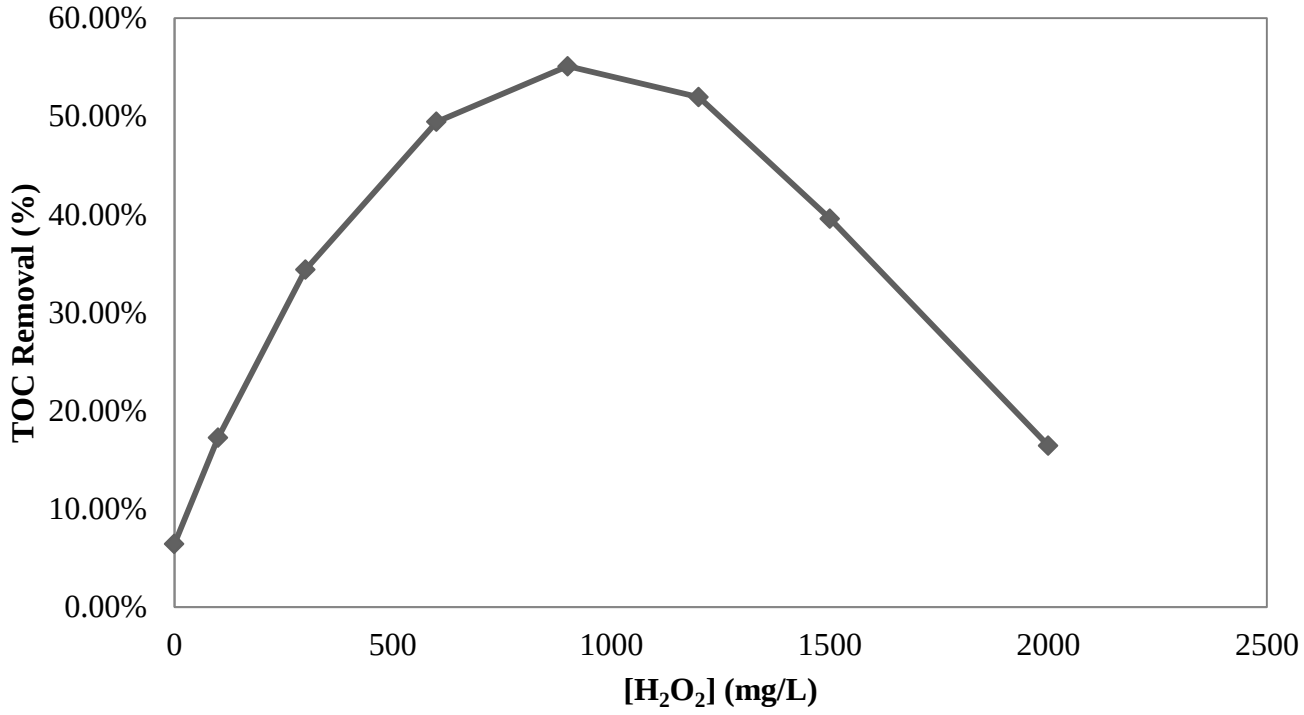


Figure E.4. Optimal Concentration of H_2O_2 for TOC removal of an influent concentration of 163.69mg/L.

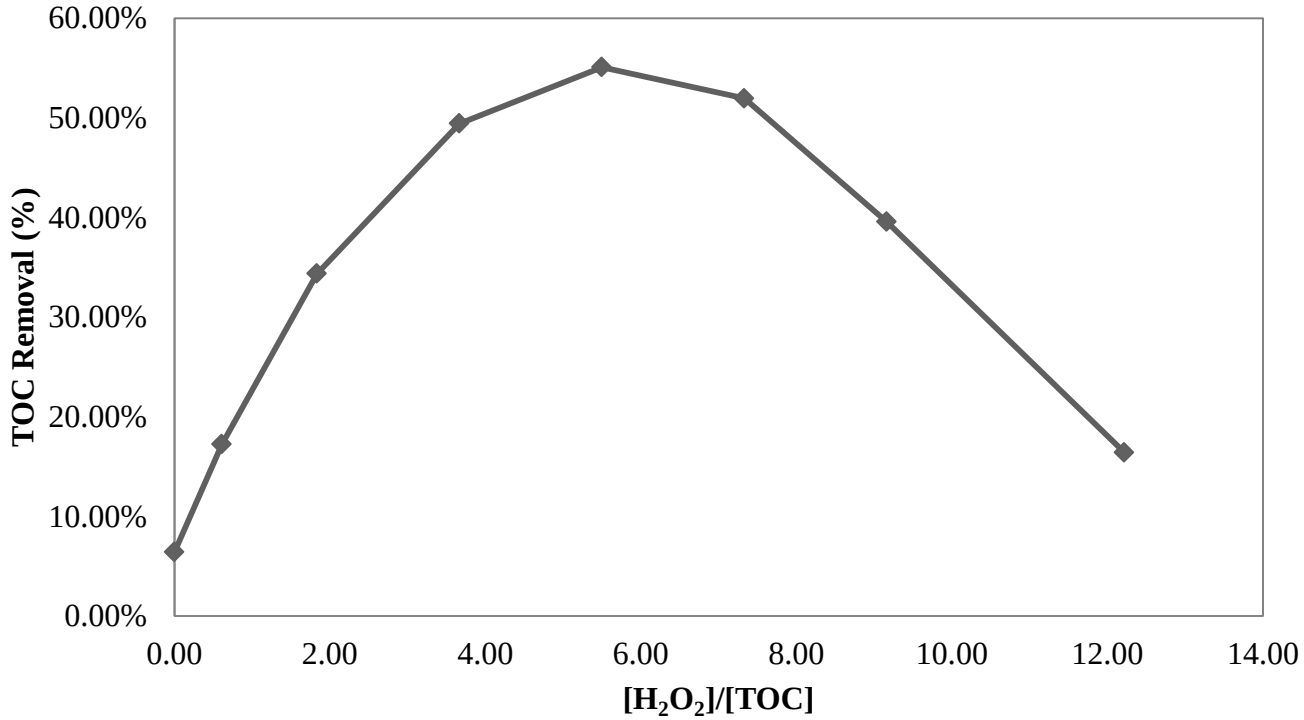


Figure E.5. Relation of molar ratio of $[H_2O_2]/[TOC]$ for an influent concentration of 163.69mg/L.

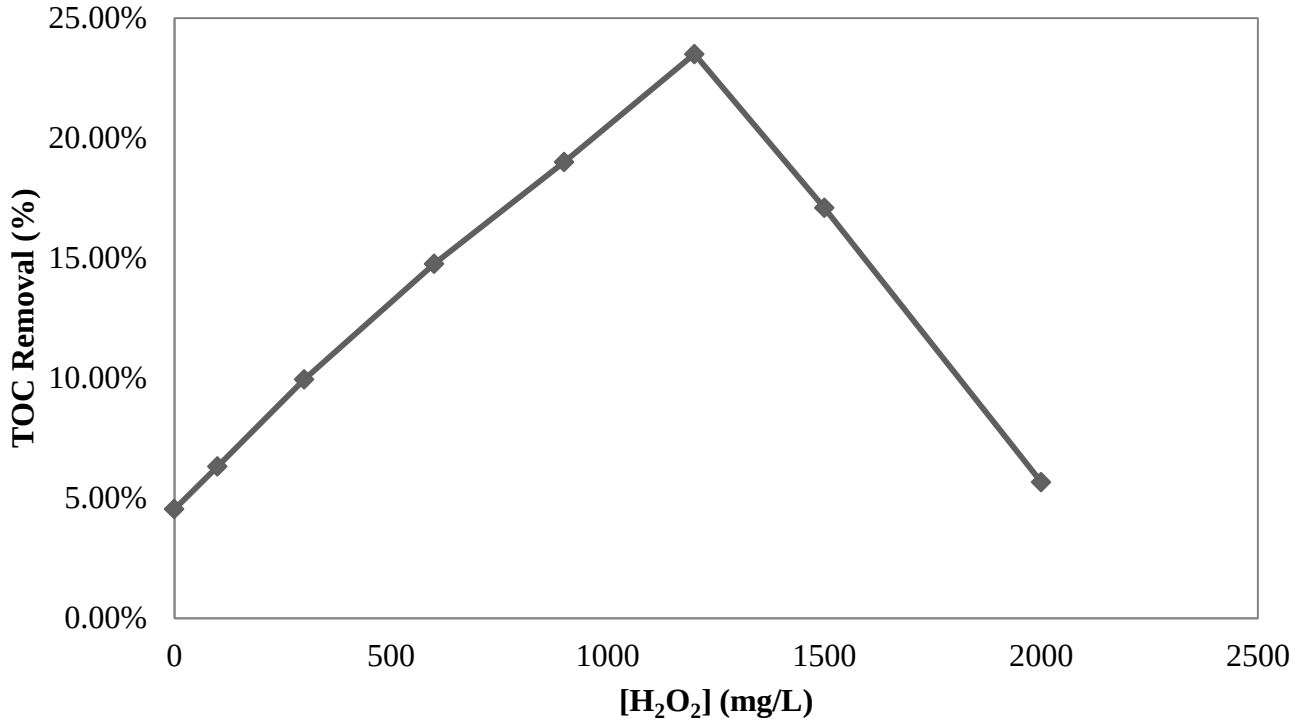


Figure E.6. Optimal Concentration of H_2O_2 for TOC removal of an influent concentration of 349.84mg/L.

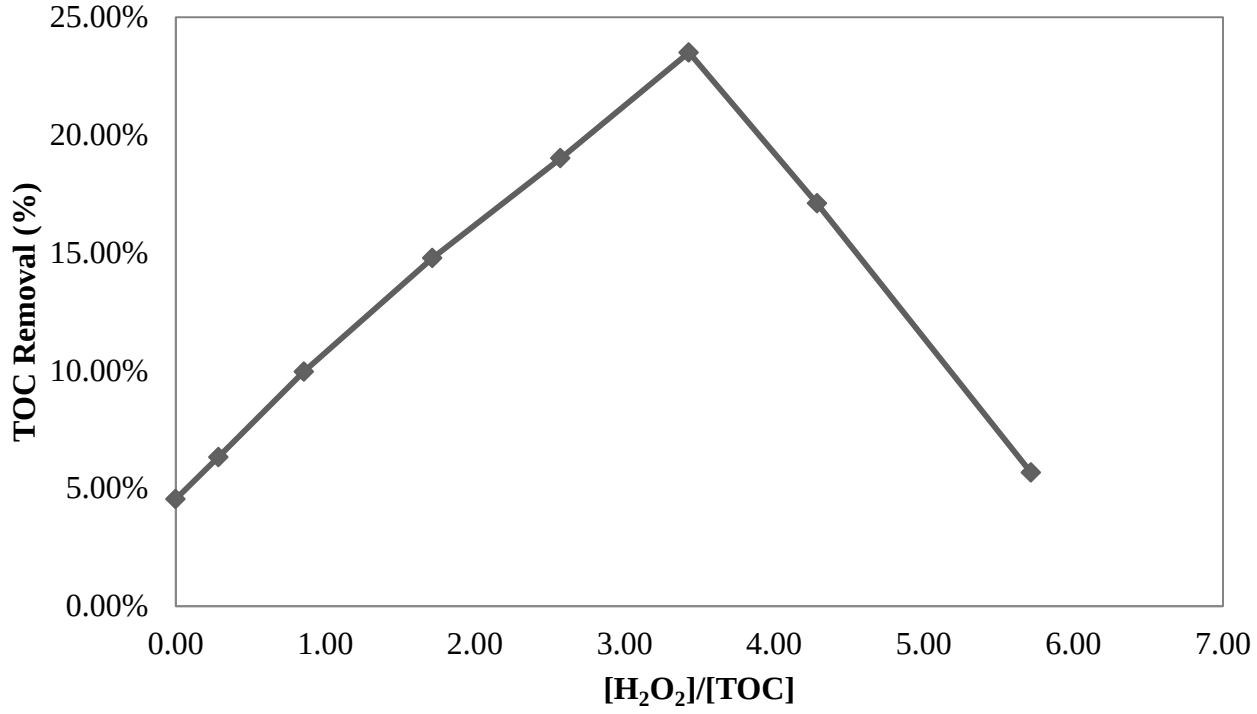


Figure E.7. Relation of molar ratio of $[H_2O_2]/[TOC]$ for an influent concentration of 349.84mg/L.

REFERENCES

Abramović, B., Banić, N., and Šojić, D. (2010). Degradation of thiacloprid in aqueous solution by UV and UV/H_2O_2 treatments. *Chemosphere, 81 (1)*, 114-119.

Adams, C., Scanlon, P., and Secrist, N. (1994). Oxidation and biodegradability enhancement of 1, 4-Dioxane using hydrogen peroxide and ozone. *Environ. Sci. Tech. 28 (11)*, 1812–1808.

Adams, C., Spitzer, S., and Cowan, R. (1996). Biodegradation of non-ionic surfactants and effects of oxidative pre-treatment. *J. Environ. Eng. 122*, 477–483.

Afzal, A., Oppenländer, T., Bolton, J., and El-Din, M. (2010). Anatoxin-a degradation by Advanced Oxidation Processes: Vacuum-UV at 172 nm, photolysis using medium pressure UV and UV/H_2O_2. *Water Res., 44 (1)*, 278-286.

Agdag, O., and Sponza, D. (2005). Anaerobic/aerobic treatment of municipal landfill leachate in sequential two-stage up-flow anaerobic sludge blanket reactor (UASB)/completely stirred tank reactor (CSTR) systems. *Process Biochem. 40*, 895–902.

Aggelis, G., Gavala, H., and Lyberatos, G. (2001). Combined, separate aerobic and anaerobic biotreatment of green olive debittering wastewater. *J. Agr. Eng. Res. 80*, 283–292.

Ahn, Y., Kang, S., Chae, S., Lee, C., Bae, B., and Shin, H. (2007). Simultaneous high-strength organic and nitrogen removal with combined anaerobic upflow bed filter and aerobic membrane bioreactor. *Desalination 202*, 114-121.

Akunna, J., and Clark, M. (2000). Performance of a granular-bed anaerobic baffled reactor (GRABBR) treating whisky distillery wastewater. *Bioresource Technol., 74 (3)*, 257-261.

Al-Mutairi, N., Al-Sharifi, F.A., and Al-Shammari, S. (2008). Evaluation study of a slaughterhouse wastewater treatment plant including contact-assisted activated sludge and DAF. *Desalination 225*, 167-175.

Amit, S., and Rupali, G. (2004). Developments in wastewater treatment methods. *Desalination, 167*, 55–63.

APHA. (1998). *Standards Methods for the Examination of Water and Wastewater.* Washington D.C.: American Water Association, Water Environment Federation.

Arslan-Alaton, I., Cokgor, E., and Koban, B. (2007). Integrated photochemical and biological treatment of a commercial textile surfactant: Process optimization, process kinetics and COD fractionation. *J. Hazard. Mater., 146 (3)*, 453-458.

Artanto, Y., McDonnell, E., Verheyen, T., Adeloju, S., and Chaffee, A. (2009). The remediation of MTE water by combined anaerobic digestion and chemical treatment. *Fuel, 88 (9)*, 1786-1792.

Asano, T., Burton, F., and and Leverenz, H. (2007). *Water Reuse: Issues, Technologies and Applications.* New York, NY: McGraw-Hill Professional.

Assalin, M., Almeida, E., and Duran, N. (2009). Combined system of activated sludge and ozonation for the treatment of Kraft e1 effluent. *Int. J. Environ. Res. Publ. Health., 6 (3)*, 1145-1154.

Aye, T., Anderson, W., and Mehrvar, M. (2003). Photocatalytic treatment of cibacron brilliant yellow 3G-P(reactive yellow 2 textile dye). *J. Environ. Sci. Health Part A 38*, 1903–1914.

Aye, T., Mehrvar, M., and Anderson, W. (2004). Effects of photocatalysis on the biodegradability of cibacron brilliant yellow 3G-P (reactive yellow 2). *J. Environ. Sci. Health Part A 39*, 113–126.

Baeza, C., Rossner, A., Jardim, W., Litter, M., and Mansilla, H. (2003). Removal of EDTA by UV-C/hydrogen peroxide. *Environ. Technol., 24 (10)*, 1277-1281.

Balcioglu, I., Arslan, I., and Sacan, M. (2001). Homogeneous and heterogeneous advanced oxidation of two commercial reactive dyes. *Environ. Technol. 22*, 813–822.

Balcioğlu, I., Saraç, C., Kivilcimdan, C., and Tarlan, E. (2006). Application of ozonation and biotreatment for forest industry wastewater. *Ozone Sci. Eng., 28 (6)*, 431-436.

Barber, W. P., and Stuckey, D. C. (1999). The use of the anaerobic baffled reactor (ABR) for wastewater treatment: a review. *Water Res. 33*, 1559-1578.

Barrera, M. (2011). *Photochemical treatment of organic constituents and bacterial pathogens from synthetic slaughterhouse wastewater by combining Vacuum-UV and UV-C.* Toronto: Ryerson University.

Barrera, M., Mehrvar, M., Gilbride, K., McCarthy, L., Laursen, A., Bostan, V., et al. (2011). Photolytic treatment of organic constituents and bacterial pathogens in secondary effluent of synthetic slaughterhouse wastewater. *Chem. Eng. Res. Des.*, Article in Press.

Barreto-Rodrigues, M. S. (2009). Combined photocatalytic and fungal processes for the treatment of nitrocellulose industry wastewater. *J. Hazard. Mater., 161 (2-3)*, 1569-1573.

Baruth, B. (2005). *Water Treatment Plant Design (4th ed.).* New York, NY: McGraw-Hill.

BC MOE. (2010). *Code of Practice for the Slaughter and Poultry Processing Industries.* Vancouver: British Columbia Ministry of Environment (BC MOE).

Bell, J., and Buckley, C. (2003). Treatment of a textile dye in the anaerobic baffled reactor. *Water SA, 29 (2),* 129-134.

Belsky, A. J., Matzke, A., and Uselman, S. (1999). Survey of livestock influences on stream and riparian ecosystems in the western United States. *J. Soil Water Conserv. 54*, 419-431.

Beltrán, F., Ovejero, G., and Acedo, B. (1993). Oxidation of atrazine in water by ultraviolet radiation combined with hydrogen peroxide. *Water Res. 27*, 1013–1021.

Ben, W., Qiang, Z., Pan, X., and Chen, M. (2009). Removal of veterinary antibiotics from sequencing batch reactor (SBR) pretreated swine wastewater by Fenton's reagent. *Water Res., 43 (17),* 4392-4402.

Benitez, F., Acero, J., Garcia, J., and Leal, A. (2003b). Purification of cork processing wastewaters by ozone, by activated sludge, and by their two sequential applications. *Water Res., 37 (17),* 4081-4090.

Benitez, F., Real, F., Acero, J., Garcia, J., and Sanchez, M. (2003a). Kinetics of the ozonation and aerobic biodegradation of wine vinasses in discontinuous and continuous processes. *J. Hazard. Mater., 101 (2),* 203-218.

Benka-Coker, M. O., and Ojior, O. O. (1995). Effect of slaughterhouse wastes on the water quality of Ikpoba River, Nigeria. *Bioresour. Technol. 52*, 5-12.

Bhatkhande, D., Pangarkar, V., and Beenackers, A. (2002). Photocatalytic degradation for environmental applications: a review. *J. Chem. Technol. Biotechnol. 77*, 102–116.

Bielski, B. H., Cabelli, D. E., and Arudi, R. L. (1985). Reactivity of HO2/O2- Radicals in Aqueous Solution. *J. Phys. Chem. Ref., 14 (4),* 1041-1100.

Bijan, L., and Mohseni, M. (2005). Integrated ozone and biotreatment of pulp mill effluent and changes in biodegradability and molecular weight distribution of organic compounds. *Water Res., 39 (16),* 3763-3772.

Black, and Veatch. (2010). *White's handbook of chlorination and alternative disinfectants (5th ed.).* Hoboken, New Jersey: John Wiley and Sons.

Bodík, I., Kratochvíl, K., Gašpariková, E., and Hutan, M. (2003). Nitrogen removal in an anaerobic baffled filter reactor with aerobic post-treatment. *Bioresource Technol., 86 (1),* 79-84.

Bolton, J., and Cotton, C. (2008). *The ultraviolet disinfection handbook (1st ed.).* Denver, TX: American Water Works Association (AWWA).

Bolton, J., Bircher, K., Tumas, W., and Tolman, C. (2001). Figures-of-merit for the technical development and application of advanced oxidation technologies for both electric- and solar-driven systems. *Pure Appl. Chem., 73 (4)*, 627-637.

Boopathy, R. (1998). Biological treatment of swine waste using anaerobic baffled reactors. *Bioresource Technol., 64 (1)*, 1-6.

Borja, R., Banks, C., and Wang, Z. (1995a). Performance of a hybrid anaerobic reactor, combining a sludge blanket and a filter, treating slaughterhouse wastewater. *Appl. Microbiol. Biotechnol., 43 (2)*, 351-357.

Borja, R., Banks, C., and Wang, Z. (1995b). Effect of organic loading rate on anaerobic treatment of slaughterhouse wastewater in a fluidised-bed reactor. *Bioresource Technol., 52 (2)*, 157-162.

Bowers, A., Gaddipati, P., Eckenfelder, J., and Monsen, R. (1989). Treatment of toxic or refractory wastewater with hydrogen peroxide. *Water Sci. Technol.*, 477–486.

Brown, N. J. (1997). *Health Hazard Manual: Wastewater Treatment Plant and Sewer Workers.* Buffalo, NY: Cornell University ILR School.

Bull, M., Sterritt, R., and Lester, J. (1982). The treatment of wastewaters from the meat industry: A review. *Environmental Technology Letters 3*, 117-126.

Buxton, G. V., Greenstock, C. L., Helman, W. P., and Ross, A. B. (1988). Critical Review of rate constants for reactions of hydrated electrons, hydrogen atoms and hydroxyl radicals (·OH/·O− in Aqueous Solution. *J. Phys. Chem. Ref. Data 17, 513*, 513-887.

Cakir, F., and Stenstrom, M. (2005). Greenhouse gas production: a comparison between aerobic and anaerobic wastewater treatment technology. *Water Res. 39*, 4197–4203.

Camin, K. (1970). Cost of waste treatment in the meat packing industry. *Proceedings of the 25th Industrial Waste Conference* (pp. 193-202). Ann Arbor, MI: Ann Arbor Science.

Cao, W. (2009). *Combined anaerobic baffled reactor and UV/H_2O_2 process for the treatment of synthetic slaughterhouse wastewater.* Toronto: Ryerson University.

Cao, W., and Mehrvar, M. (2011). Slaughterhouse wastewater treatment by combined anaerobic baffled reactor and UV/H_2O_2 processes. *Chem. Eng. Res. Des., 89 (7)*, 1136-1143.

Carey, J. (1990). An introduction to advanced oxidation processes (AOP) for destruction of organics in wastewater. *Proceedings of the Symposium on Advanced Oxidation Process for Contaminated Water and Air.* Toronto.

Cassidy, D., and Belia, E. (2005). Nitrogen and phosphorus removal from an abattoir wastewater in a SBR with aerobic granular sludge. *Water Res., 39 (19)*, 4817-4823.

Castillo, A., Llabres, P., and Mata-Alvarez, J. (1999). A kinetic study of a combined anaerobic–aerobic system for treatment of domestic sewage. *Water Res. 33*, 1742–1747.

Cater, S., Stefan, M., Bolton, J., and Safarzadeh-Amiri, A. (2000). UV/H_2O_2 treatment of methyl t-butyl ether in contaminated waters. *Environ. Sci. Tech. 34*, 659–662.

CEC. (1991). Urban Wastewater Treatment Directive 91/271/EEC, Council of the European Communities (CEC). *Off. J. Eur. Comm. 30. 5. 91*, L 135/40-52.

Cervantes, F., Pavlostathis, S., and Haandel, A. v. (2006). *Advanced Biological Treatment Processes for Industrial Wastewaters: Principles and Applications.* London, UK: IWA Publishing.

Chan, Y. J., Chong, M. F., Law, C. L., and Hassell, D. (2009). A review on anaerobic-aerobic treatment of industrial and municipal wastewater. *Chem. Eng. J. 155*, 1-18.

Chelikani, P., Fita, I., and Loewen, P. (2004). Diversity of structures and properties among catalases. *Cell. Mol. Life Sci., 61 (2)*, 192-208.

Chen, C.-Y., Wu, P.-S., and Chung, Y.-C. (2009). Coupled biological and photo-Fenton pretreatment system for the removal of di-(2-ethylhexyl) phthalate (DEHP) from water. *Bioresource Technol., 100 (19)*, 4531-4534.

Chen, H. (2004). ATP content and biomass activity in sequential anaerobic/aerobic reactors. *J. Zhejiang Univ. Sci. 5*, 727–732.

Chen, K.-C., and Lin, Y.-F. (1993). The relationship between denitrifying bacteria and methanogenic bacteria in a mixed culture system of acclimated sludges. *Water Res., 27 (12)*, 1749-1759.

Chernicharo, C. (2006). Post-treatment options for the anaerobic treatment of domestic wastewater. *Review. Environ. Sci. Biotechnol. 5*, 73-92.

Christensen, H., Sehested, K., and Corfitzen, H. (1982). Reactions of hydroxyl radicals with hydrogen peroxide at ambient and elevated temperatures. *J. Phys. Chem., 86 (9)*, 1588-1590.

Clarke, N., and Knowles, G. (1982). High purity water using H2O2 and UV radiation. *Effluent Water Treat. J.*, 335–341.

Comninellis, C., Kapalka, A., Malato, S., Parsons, S., Poulios, I., and Mantzavinos, D. (2008). Perspective - Advanced Oxidation Processes for water treatment: advances and trends for R&D. *J. Chem. Technol. Biotechnol. 83*, 769–776.

Crittenden, J., Hu, S., Hand, D., and Green, S. (1999). A kinetic model for H2O2/UV process in a completely mixed batch reactor. *Water Res. 33*, 2315-2328.

De Morais, J., and Zamora, P. (2005). Use of advanced oxidation processes to improve the biodegradability of mature landfill leachates. *J. Hazard. Mater. 123*, 181–186.

de Sena, R., Tambosi, J., Genena, A., Moreira, R., Schröder, H., and José, H. (2009). Treatment of meat industry wastewater using dissolved air flotation and advanced oxidation processes monitored by GC-MS and LC-MS. *Chem. Eng. J., 152 (1)*, 151-157.

Debik, E., and Coskun, T. (2009). Use of the Static Granular Bed Reactor (SGBR) with anaerobic sludge to treat poultry slaughterhouse wastewater and kinetic modeling. *Bioresour. Technol. 100 (11)*, 2777-2782.

Del Pozo, and Diez, V. (2003). Organic matter removal in combined anaerobic–aerobic fixed-film bioreactors. *Water Res. 37*, 3561–3568.

del Pozo, R. D. (2000). Anaerobic pre-treatment of slaughterhouse wastewater using fixed-film reactors. *Bioresource Technol., 71 (2)*, 143-149.

Del Pozo, R., and Diez, V. (2005). Integrated anaerobic-aerobic fixed-film reactor for slaughterhouse wastewater treatment. *Water Res. 39*, 1114-1122.

Del Pozo, R., Taş, D., Dulkadiroğlu, H., Orhon, D., and Diez, V. (2003). Biodegradability of slaughterhouse wastewater with high blood content under anaerobic and aerobic conditions. *J. Chem. Technol. Biotechnol., 78 (4)*, 384-391.

Devipriyas, S., and Yesodharan, S. (2005). Photocatalytic degradation of pesticide contaminants in water. *Sol. Energy Mater. Sol. Cells 86*, 309–348.

Di Iaconi, C., Lopez, A., Ramadori, R., Di Pinto, A., and Passino, R. (2002). Combined chemical and biological degradation of tannery wastewater by a periodic submerged filter (SBBR). *Water Res., 36 (9)*, 2205-2214.

Dogruel, S., Genceli, E., Babuna, F., and Orhon, D. (2006). An investigation on the optimal location of ozonation within biological treatment for a tannery wastewater. *J. Chem. Technol. Biotechnol., 81 (12)*, 1877-1885.

Durán, A., Monteagudo, J., and San Martín, I. (2012). Photocatalytic treatment of an industrial effluent using artificial and solar UV radiation: An operational cost study on a pilot plant scale. *J. Environ. Manage., 98 (1)*, 1-4.

Eckstein, T. (1994). *Sequential advanced oxidation–biodegradation of simple aqueous solutions of aromatic compounds.* Chapel Hill, NC: University of North Carolina.

ECO. (2010). *Sewage Treatment: Not Good Enough.* Toronto: Environmental Commissioner of Ontario (ECO). The Queen's Printer for Ontario.

Edalatmanesh, M., Mehrvar, M., and Dhib, R. (2008). Optimization of phenol degradation in a combined photochemical-biological wastewater treatment system. *Chem. Eng. Res. Des. 86*, 1243-1252.

Entezari, M., and Pétrier, C. (2003). A combination of ultrasound and oxidative enzyme: Sono-biodegradation of substituted phenols. *Ultrason. Sonochem., 10 (4-5),* 241-246.

Environment Canada. (2000). *Framework and recommendations concerning effluent quality of wastewater disposed by federal institutions.* Retrieved December 10, 2010, from FCEMS/Wastewater Working Group: http://www.csc-scc.gc.ca/text/plcy/doc/318-6-gl_e.pdf

Fang, L. (2000). Environmental Effects of the Beef Industry. *Agricultural and Natural Resource Economics Discussion Paper Series.* Queensland, Australia: School of Natural and Rural Systems Management University of Queensland.

Fdez-Polanco, F., Real, F., and Garcia, P. (1994). Behavior of an anaerobic/aerobic pilotscale fluidized-bed for the simultaneous removal of carbon and nitrogen. *Water Sci. Technol. 29,* 339–346.

Feng, H., Hu, L., Mahmood, Q., Fang, C., Qiu, C., and Shen, D. (2009). Effects of temperature and feed strength on a carrier anaerobic baffled reactor treating dilute wastewater. *Desalination 239,* 111-121.

Foxon, K., Pillay, S., Lalbahadur, T., Rodda, N., Holder, F., and Buckley, C. (2004). The anaerobic baffled reactor (ABR): An appropriate technology for on-site sanitation. *Water SA, 30 (5),* 592-598.

Frostell, B. (1983). Anaerobic–Aerobic Biological Treatment of Starch Industry Waste Waters. *Starch—Stärke 35,* 185–189.

Fuchs, W., Binder, H., Mavrias, G., and Braun, R. (2003). Anaerobic treatment of wastewater with high organic content using a stirred tank reactor coupled with a membrane filtration unit. *Water Res., 37 (4),* 902-908.

Garbossa, L., Lapa, K., Zaiat, M., and Foresti, E. (2005). Development and evaluation of a radial anaerobic/aerobic reactor treating organic matter and nitrogen in sewage. *Braz. J. Chem. Eng. 22,* 511–519.

García, M., Ribosa, I., Guindulain, T., Sánchez-Leal, J., and Vives-Rego, J. (2001). Fate and effect of monoalkyl quaternary ammonium surfactants in the aquatic environment. *Environ. Pollut. 111,* 169–175.

García-Montaño, J., Domènech, X., García-Hortal, J., Torrades, F., and Peral, J. (2008). The testing of several biological and chemical coupled treatments for Cibacron Red FN-R azo dye removal. *J. Hazard. Mater., 154 (1-3),* 484-490.

García-Montaño, J., Ruiz, N., Muñoz, I., Doménech, X., García-Hortal, J., and Torrades, F. (2006). Environmental assessment of different photo-Fenton approaches for commercial reactive dye removal. *J. Hazard. Mater. Part A 138*, 218–225.

Gariepy, S., Tyagi, R. D., Couillard, D., and Tran, F. (1989). Thermophilic Process for Protein Recovery as an Alternative to Slaughterhouse Wastewater Treatment. *Biological Wastes 29*, 93-105.

Gerardi, M. H. (2002). *Nitrification and Denitrification in the Activated Sludge Process.* New York: John Wiley and Sons, Inc.

Gizgis, N., Georgiou, M., and Diamadopoulos, E. (2006). Sequential anaerobic/aerobic biological treatment of olive mill wastewater and municipal wastewater. *J. Chem. Technol. Biotechnol. 81*, 1563–1569.

Glaze, W. (1987). Drinking-water treatment with ozone. *Environ. Sci. Technol. 21*, 224–230.

Glaze, W., Lay, Y., and Kang, J. (1995). Advanced oxidation processes: a kinetic model for the oxidation of 1-2 dibromo 3-chloropropane in water by the combination of hydrogen peroxide and UV radiation. *Ind. Eng. Chem. Res. 34*, 2314–2323.

Gogate, P., and Pandit, A. (2004a). A review of imperative technologies for wastewater treatment I: oxidations technologies at ambient conditions. *Adv. Environ. Res. 8*, 501–551.

Gogate, P., and Pandit, A. (2004b). A review of imperative technologies for wastewater treatment II: hybrid methods. *Adv. Environ. Res. 8*, 553–597.

Gonzalez, M., Braun, A., Bianco Prevot, A., and Pelizzetti, E. (1994). Vacuum-ultraviolet (VUV) photolysis of water: Mineralization of atrazine. *Chemosphere, 28 (12)*, 2121-2127.

Gonze, E., Commenges, N., Gonthier, Y., and Bernis, A. (2003). High frequency ultrasound as a pre- or post-oxidation for paper mill wastewaters and landfill leachate treatment. *J. Chem. Eng. 92*, 215–225.

Goslan, E., Gurses, F., Banks, J., and Parsons, S. (2006). An investigation into reservoir NOM reduction by UV photolysis and advanced oxidation processes. *Chemosphere, 65 (7)*, 1113-1119.

Grady, C. P., Daigger, G. T., and Lim, H. C. (1999). *Biological Wastewater Treatment, second ed. revised and expanded.* CRC Press.

Gray, N. (2005). *Water Technology: An Introduction for Environmental Scientists and Engineers.* Oxford: Elsevier.

Grover, R., Marwaha, S., and Kennedy, J. (1999). Studies on the use of an anaerobic baffled reactor for the continuous anaerobic digestion of pulp and paper mill black liquors. *Process Biochem., 34 (6-7)*, 653-657.

Gulyas, H., Choromanski, P., Muelling, N., and Furmanska, M. (2009). Toward chemical-free reclamation of biologically pretreated greywater: solar photocatalytic oxidation with powdered activated carbon. *J. Cleaner Prod., 17 (13)*, 1223-1227.

Halweil, B. (2008). *Vital signs: Meat production continues to rise.* Washington, DC: World Watch Institute.

Hano, T., Matsumoto, M., Kuribayashi, K., and Hatate, Y. (1992). Biological nitrogen removal in a bubble column with a draught tube. *Chem. Eng. Sci. 47*, 3737–3744.

Heijnen, J., Mulder, A., Weltevrede, R., Hols, J., and Vanleeuwen, H. (1991). Large-scale anaerobic–aerobic treatment of complex industrial-waste water using biofilm reactors. *Water Sci. Technol. 23*, 1427–1436.

Hu, S., and Yu, Y. (1994). Preozonation of chlorophenolic wastewater for subsequent biological treatment. *Ozone-Sci. Eng. 16*, 13–28.

IJC. (2009). *Fourteenth Biennial Report on Great Lakes Water Quality.* Windsor, ON: International Joint Commission.

Isik, and Sponza, D. T. (2004). Anaerobic/aerobic sequential treatment of a cotton textile mill wastewater. *J. Chem. Technol. Biotechnol. 79*, 1268–1274.

Isik, M., and Sponza, D. (2006). Biological treatment of acid dyeing wastewater using a sequential anaerobic/aerobic reactor system. *Enzyme Microb. Technol. 38*, 887–892.

Isik, M., and Sponza, D. (2008). Anaerobic/aerobic treatment of a simulated textile wastewater. *Sep. Purif. Technol. 60*, 64–72.

Johns, M. (1995). Developments in wastewater treatment in the meat processing industry: A review. *Bioresour. Technol. 54*, 203-216.

Johnson, M., and Mehrvar, M. (2008). Aqueous metronidazole degradation by UV/H_2O_2 process in single-and multi-lamp tubular photoreactors: Kinetics and reactor design. *Ind. Eng. Chem. Res., 47 (17)*, 6525-6537.

Jones, B., Sakaji, R., and Daughton, C. (1985). Effects of ozonation and ultraviolet irradiation on biodegradability of oil shale wastewater organic solutes. *Water Res. 19*, 1421–1428.

Justino, C., Duarte, K., Loureiro, F., Pereira, R., Antunes, S., Marques, S., et al. (2009). Toxicity and organic content characterization of olive oil mill wastewater undergoing a sequential treatment with fungi and photo-Fenton oxidation. *J. Hazard. Mater., 172 (2-3)*, 1560-1572.

Kapdan, I., and Alparslan, S. (2005). Application of anaerobic–aerobic sequential treatment system to real textilewastewater for color and COD removal. *Enzyme Microb. Technol. 36*, 273–79.

Kastanek, F., Maleterova, Y., and Kastanek, P. (2007). Combination of advanced oxidation and/or reductive dehalogenation and biodegradation for the decontamination of waters contaminated with chlorinated organic compounds. *Sep. Sci. Technol., 42 (7)*, 1613-1625.

Kennedy, K., and Barriault, M. (2007). Treatment kinetics of aircraft deicing fluid in an anaerobic baffled reactor. *J. Environ. Eng. Sci., 6 (1)*, 11-17.

Kettunen, R., and Rintala, J. (1995). Sequential anaerobic-aerobic treatment of sulphur rich phenolic leachates. *J. Chem. Technol. Biotechnol. 62*, 177–184.

Kim, I., Kim, S., Lee, H., and Tanaka, H. (2011). Effects of adding UV and H2O2 on the degradation of pharmaceuticals and personal care products during O3 treatment. *Environ. Eng. Res., 16 (3)*, 131-136.

Kim, I., Yamashita, N., and Tanaka, H. (2009a). Performance of UV and UV/H_2O_2 processes for the removal of pharmaceuticals detected in secondary effluent of a sewage treatment plant in Japan. *J. Hazard. Mater., 166 (2-3)*, 1134-1140.

Kim, I., Yamashita, N., and Tanaka, H. (2009b). Photodegradation of pharmaceuticals and personal care products during UV and UV/H_2O_2 treatments. *Chemosphere, 77 (4)*, 518-525.

Kim, T.-H., Park, C., Lee, J., Shin, E.-B., and Kim, S. (2002). Pilot scale treatment of textile wastewater by combined process (fluidized biofilm process-chemical coagulation-electrochemical oxidation). *Water Res., 36 (16)*, 3979-3988.

Kingsley, O. C. (2011). *Using Life Cycle Assessment (LCA) to Assess the Sustainability of Urban Wastewater Treatment Systems: a Case Study of the Wastewater Treatment Technology of the Bogotá River*. Bogota, Colombia: Universidad Nacional de Colombia.

Klavarioti. (2009). Removal of residual pharmaceuticals from aqueous systems by advanced oxidation processes. *Environ. Int. 35*, 402–417.

Koppenol, W. H., Butler, J., and Van Leeuwen, J. W. (1978). The Haber-Weiss Cycle. *J. Photochem. Photobiol., 28*, 655–660.

Kotsou, M., Kyriacou, A., Lasaridi, K., and Pilidis, G. (2004). Integrated aerobic biological treatment and chemical oxidation with Fenton's reagent for the processing of green table olive wastewater. *Process Biochem., 39 (11)*, 1653-1660.

Koyama, O., Kamayat, Y., and Nakamura, K. (1994). Degradation of chlorinated aromatics by Fenton oxidation and methanogenic digester sludge. *Water Res. 28*, 895–899.

Krishna, G. G., Kumar, P., and Kumar, P. (2009). Treatment of low-strength soluble wastewater using an anaerobic baffled reactor (ABR). *J. Environ. Manage. 90,* 166-176.

Ku, Y., Wang, L., and Shen, Y. (1998). Decomposition of EDTA in aqueous solution by UV/H_2O_2 process. *J. Hazard. Mater.*, 41-55.

Kuşçu, Ö., and Sponza, D. (2005). Performance of anaerobic baffled reactor (ABR) treating synthetic wastewater containing p-nitrophenol. *Enzyme and Microbial Technology, 36 (7),* 888-895.

Kuşçu, O., and Sponza, D. (2006). Treatment efficiencies of a sequential anaerobic baffled reactor (ABR)/completely stirred tank reactor (CSTR) system at increasing p-nitrophenol and COD loading rates. *Process Biochem., 41 (7),* 1484-1492.

Kyriacou, A., Lasaridi, K., Kotsou, M., Balis, C., and Pilidis, G. (2005). Combined bioremediation and advanced oxidation of green table olive processing wastewater. *Process Biochem., 40 (3-4),* 1401-1408.

La Motta, E., Silva, E., Bustillos, A., Padron, H., and Luque, J. (2007). Combined anaerobic/aerobic secondary municipal wastewater treatment: Pilot-plant demonstration of the UASB/aerobic solids contact system. *J. Environ. Eng. - ASCE 133*, 397–403.

L'Amour, R., Azevedo, E., Leite, S., and Dezotti, M. (2008). Removal of phenol in high salinity media by a hybrid process (activated sludge + photocatalysis). *Sep. Purif. Technol., 60 (2),* 142-146.

Langenhoff, A., Intrachandra, N., and Stuckey, D. (2000). Treatment of dilute soluble and colloidal wastewater using an anaerobic baffled reactor: Influence of hydraulic retention time. *Water Res., 34 (4),* 1307-1317.

Lapertot, M., Pulgarín, C., Fernández-Ibañez, P., Maldonado, M., Pérez-Estrada, L., and Oller, I. (2006). Enhancing biodegradability of priority substances (pesticides) by solar photo- Fenton. *Water Res. 40*, 1086–1094.

Lee, L., Ng, H., Ong, S., Hu, J., Tao, G., Kekre, K., et al. (2009). Ozone-biological activated carbon as a pretreatment process for reverse osmosis brine treatment and recovery. *Water Res., 43 (16),* 3948-3955.

Lee, S., and Carberry, J. (1992). Biodegradation of PCP enhanced by chemical oxidation pre-treatment. *Water Environ. Res. 64*, 682–690.

Lei, Y., Shen, Z., Huang, R., and Wang, W. (2007). Treatment of landfill leachate by combined aged-refuse bioreactor and electro-oxidation. *Water Res., 41 (11),* 2417-2426.

Leitao, R., Haandel, A., Zeeman, G., and Lettinga, G. (2006). The effects of operational and environmental variations on anaerobic wastewater treatment systems: A review. *Bioresour. Technol. 97*, 1105–1118.

Li, K., Stefan, M., and Crittenden, J. (2007). Trichloroethene degradation by UV/H_2O_2 advanced oxidation process: Product study and kinetic modeling. *Environ. Sci. Technol., 41 (5)*, 1696-1703.

Libra, J., and Sosath, F. (2003). Combination of biological and chemical processes for the treatment of textile wastewater containing reactive dyes. *J. Chem. Technol. Biotechnol., 78 (11)*, 1149-1156.

Liu, H., Yang, C., Pu, W., and Zhang, J. (2008). Removal of nitrogen fromwastewater for reusing to boiler feed-water by an anaerobic/aerobic/membrane bioreactor. *Chem. Eng. J. 140*, 122–129.

Lo, K., and Liao, P. (1986). Anaerobic aerobic biological treatment of screened dairy manure. *Biomass 10*, 187–193.

Lo, K., and Liao, P. (1989). Anaerobic–aerobic biological treatment of amixture of cheese whey and dairy manure. *Biological Wastes 28*, 91-101.

López-Peñalver, J., Sánchez-Polo, M., Gómez-Pacheco, C., and Rivera-Utrilla, J. (2010). Photodegradation of tetracyclines in aqueous solution by using UV and UV/H_2O_2 oxidation processes. *J. Chem. Technol. Biotechnol., 85 (10)*, 1325-1333.

Luiz, D., Genena, A., José, H., Moreira, R., and Schröder, H. (2009). Tertiary treatment of slaughterhouse effluent: Degradation kinetics applying UV radiation or H2O2/UV. *Water Sci. Technol., 60 (7)*, 1869-1874.

Manjunath, N., Mehrotra, I., and Mathur, R. (2000\). Treatment of wastewater from slaughterhouse by DAF-UASB system. *Water Res., 34 (6)*, 1930-1936.

Mänttäri, M., Kuosa, M., Kallas, J., and Nyström, M. (2008). Membrane filtration and ozone treatment of biologically treated effluents from the pulp and paper industry. *J. Membr. Sci., 309 (1-2)*, 112-119.

Mascolo, G., Laera, G., Pollice, A., Cassano, D., Pinto, A., Salerno, C., et al. (2010). Effective organics degradation from pharmaceutical wastewater by an integrated process including membrane bioreactor and ozonation. *Chemosphere, 78 (9)*, 1100-1109.

Masse, D., and Masse, L. (2000a). Treatment of slaughterhouse wastewater in anaerobic sequencing batch reactors. *Can. Agr. Eng. 42*, 131-137.

Masse, D., and Masse, L. (2000b). Characterization of wastewater from hog slaughterhouses in Eastern Canada and evaluation of their in-plant wastewater treatment systems. *Can. Agr. Eng. 42 (3)*, 139-146.

Matsumura, E., and Mierzwa, J. (2008). Water conservation and reuse in poultry processing plant – a case study. *Resour. Conser. Recy. 52 (6)*, 835–842.

McMurray, J., and Fay, R. (1998). *Chemistry (5th ed.).* Upper Saddle River, NJ: Pearson Prentice-Hall.

Mehrvar, M., Anderson, W., and Moo-Young, M. (2001). Photocatalytic degradation of aqueous organic solvents in the presence of hydroxyl radical scavengers. *Int. J. Photoenergy, 3 (4)*, 187-191.

Merzouki, M., Bernet, N., Delgenès, J., and Benlemlih, M. (2005). Effect of prefermentation on denitrifying phosphorus removal in slaughterhouse wastewater. *Bioresource Technol., 96 (12)*, 1317-1322.

Miguez, C., Shen, C., Bourque, D., Guiot, S., and Grouleau, D. (1999). Monitoring methanotrophic bacteria in hybrid anaerobic–aerobic reactors with PCR and a catabolic gene probe. *Appl. Environ. Microbiol. 65*, 381–388.

Miller, R., Singer, G., Rosen, J., and Bartha, R. (1988). Sequential degradation of chlorophenols by photolytic and microbial treatment. *Environ. Sci. Tech. 22*, 1215–1209.

Mittal, G. (2006). Treatment of wastewater from abattoirs before land application - A review. *Bioresource Technol., 97 (9)*, 1119-1135.

Mohajerani, M., Mehrvar, M., and Ein-Mozaffari, F. (2009). An overview of the integration of advanced oxidation technologies and other processes for wastewater treatment. *Int. J. Eng. 3*, 120–146.

Moosavi, G., Mesdaghinia, A., Naddafi, K., and Mahvi, A. (2004). Feasibility of development and application of an up-flow anaerobic/aerobic fixed bed combined reactor to treat high strength wastewaters. *10th World Congress on Anaerobic Digestion*, (pp. 2436–2440). Montreal, QC.

Mouthon-Bello, J., and Zhou, H. (2006). Performance of a submerged membrane bioreactor system for biological nutrient removal. *Water Environ. Res., 78 (5)*, 538-547.

Muñoz, D. (2005). Sistema de Tratamiento de Aguas Residuales de Matadero: Para una Población Menor 2000 Habitantes. System of Residual Water Treatment of Slaughter House: For a Smaller Population 2000 Inhabitants. *Facultad de Ciencias Agropecuarias 3*, 87-98.

Muñoz, R., and Guieysee, B. (2006). Algal–bacterial processes for the treatment of hazardous contaminants: a review. *Water Res. 40*, 2799–2815.

Nachaiyasit, S., and Stuckey, D. (1997). Effect of low temperatures on the performance of an anaerobic baffled reactor (ABR). *J. Chem. Technol. Biotechnol., 69 (2),* 276-284.

Nadarajah, N., Van Hamme, J., Pannu, J., Singh, A., and Ward, O. (2002). Enhanced transformation of polycyclic aromatic hydrocarbons using a combined Fenton's reagent, microbial treatment and surfactants. *Appl. Microbiol. Biotechnol., 59 (4-5),* 540-544.

Nemerow, N. (2007). *Industrial Waste Treatment.* Burlington, MA: Elsevier Science and Tecnology.

Neyens, E., and Baeyens, J. (2003). A review of classic Fenton's peroxidation as an advanced oxidation technique. *J. Hazard. Mater. 98,* 33–50.

Núñez, L., Fuente, E., Martínez, B., and García, P. (1999). Slaughterhouse wastewater treatment using ferric and aluminium salts and organic polyelectrolites. *J. Environ. Sci. Health A Tox. Hazard Subst. Environ. Eng., 34 (3),* 721-736.

OEB. (2011, November 1). *Ontario Energy Board - Electricity Prices at a Glance*. Retrieved March 1, 2012, from http://www.ontarioenergyboard.ca/OEB/Consumers/Electricity/Electricity+Prices

Oller, I., Malato, S., and Sanchez-Perez, J. (2011). Combination of Advanced Oxidation Processes and biological treatments for wastewater decontamination - A review. *Sci. Total Environ., 409 (20),* 4141-4166.

OMAFRA. (2011, December 20). *Provincially Licensed Meat Plants in Ontario.* Retrieved January 31, 2012, from Ontario Ministry of Agricultural and Rural Affairs (OMAFRA): http://www.omafra.gov.on.ca/english/food/inspection/maps/MeatPlantTables/TblAllAbattoirs.htm

OMOE. (1996). *Guidelines for the Utilization of Biosolids and other Wastes on Agricultural Land.* Retrieved June 27, 2012, from Ontario Ministry of Environment (OMOE): http://www.ene.gov.on.ca/stdprodconsume/groups/lr/@ene/@resources/documents/resource/std01_079003.pdf

Oppenländer, T. (2003). *Photochemical purification of water and air, Advanced Oxidation Processes (AOPs): Principles, reaction mechanisms, reactor concepts.* Winheim, Germany: Wiley-VCH.

Pagano, M., Lopez, A., Volpe, A., Mascolo, G., and Ciannarella, R. (2008). Oxidation of nonionic surfactants by Fenton and H2O 2/UV processes. *Environ.l Technol., 29 (4),* 423-433.

Park, S.-J., Yoon, T.-I., Bae, J.-H., Seo, H.-J., and Park, H.-J. (2001). Biological treatment of wastewater containing dimethyl sulphoxide from the semi-conductor industry. *Process Biochem., 36 (6),* 579-589.

Pera-Titus, M., García-Molina, V., Baños, M., Giménez, J., and Espulgas, S. (2007). Degradation of chlorophenols by means of advanced oxidation processes: a general review. *Appl. Catal. B-Environ. 47*, 219–256.

Pignatello, J., Oliveros, E., and MacKay, A. (2006). Advanced oxidation processes for organic contaminant destruction based on the Fenton reaction and related chemistry. *Crit. Rev. Environ. Sci. Technol. 36*, 1-84.

Pittier, P., and Chudoba, J. (1990). *Biodegradability of Organic Substances in the Aquatic Environment.* Boca Raton, FL: CRC Press.

Polprasert, C., Kemmadamrong, P., and Tran, F. (1992). Anaerobic baffle reactor (ABR) process for treating a slaughterhouse wastewater. *Environ. Technol., 13 (9)*, 857-865.

Poole, A. (2004). Treatment of biorefractory organic compounds in wool scour effluent by hydroxyl radical oxidation. *Water Res., 38 (14-15)*, 3458-3464.

Pophali, G., Khan, R., Dhodapkar, R., Nandy, T., and Devotta, S. (2007). Anaerobic–aerobic treatment of purified terephthalic acid (PTA) effluent; a techno-economic alternative to two-stage aerobic process. *J. Environ. Manage. 85*, 1024–1033.

Prando, R., and Gambogi, A. (2009). *Water resources in Uruguay. Main features and challenges towards their sustainable use.* Retrieved December 5, 2010, from http://www.acad-eng-gen.ca/documents/Session%204/Prando_Gambogi.pdf

Pulgarín, C., and Kiwi, J. (1996). Overview on photocatalytic and electrocatalytic pretreatment of industrial non-biodegradable pollutants and pesticides. *Chimia 50*, 50–55.

Pulgarin, C., Invernizzi, M., Parra, S., Sarria, V., Polania, R., and Peringer, P. (1999). Strategy for the coupling of photochemical and biological flow reactors useful in mineralization of biorecalcitrant industrial pollutants. *Catal. Today 54*, 341-352.

Quinete, N., Orata, F., Maes, A., Gehron, M., Bauer, K.-H., Moreira, I., et al. (2010). Degradation studies of new substitutes for perfluorinated surfactants. *Arch. Environ. Contam. Toxicol., 59 (1)*, 20-30.

Quinn, J., and McFarlane, P. (1989). Effects of slaughterhouse and dairy factory wastewaters on epilithon: A comparison in laboratory streams. *Water Res. 23*, 1267-1273.

Rafin, C., Veignie, E., Fayeulle, A., and Surpateanu, G. (2009). Benzo[a]pyrene degradation using simultaneously combined chemical oxidation, biotreatment with Fusarium solani and cyclodextrins. *Bioresource Technol., 100 (12)*, 3157-3160.

Rajakumar, R., Meenambal, T., Banu, J. R., and Yeom, I. (2011). Treatment of poultry slaughterhouse wastewater in upflow anaerobic filter under low upflow velocity. *Int. J. Environ. Sci. Technol. 8*, 149-158.

Rajakumar, R., Meenambal, T., Banu, J. R., and Yeom, I. (2011). Treatment of poultry slaughterhouse wastewater in upflow anaerobic filter under low upflow velocity. *International journal of Environmental Science and Technology 8*, 149-158.

Rajesh Banu, J., Anandan, S., Kaliappan, S., and Yeom, I.-T. (2008). Treatment of dairy wastewater using anaerobic and solar photocatalytic methods. *Sol. Energy, 82 (9)*, 812-819.

Reginatto, V., Teixeira, R., Pereira, F., Schmidell, W., Furigo Jr., A., Menes, R., et al. (2005). Anaerobic ammonium oxidation in a bioreactor treating slaughterhouse wastewater. *Braz. J. Chem. Eng., 22 (4)*, 593-600.

Reungoat, J., Macova, M., Escher, B., Carswell, S., Mueller, J., and Keller, J. (2010). Removal of micropollutants and reduction of biological activity in a full scale reclamation plant using ozonation and activated carbon filtration. *Water Res., 44 (2)*, 625-637.

Reynolds, T., and Richards, P. (1996). *Unit Operations and Processes in Environmental Engineering, 2nd ed.* Boston, MA: PWS Publishing Company.

Reynolds, T., and Yang, J. (1966). Model of the completely-mixed activated sludge process. *Proc. 21st Ind. Waste Conf., Purdue Univ. Part 2*, 696-713.

Rizzo, L., Rocca, C., Belgiorno, V., and Bekbolet, M. (2008). Application of photocatalysis as a post treatment method of a heterotrophic-autotrophic denitrification reactor effluent. *Chemosphere, 72 (11)*, 1706-1711.

Rodriguez-Martinez, J., Rodriguez-Garza, I., Pedraza-Flores, E., Balagurusamy, N., Sosa-Santillan, G., and Garza-Garcia, Y. (2002). Kinetics of anaerobic treatment of slaughterhouse wastewater in batch and upflow anaerobic sludge blanket reactor. *Bioresource Technology 85*, 235–241.

Ros, M., and Zupancic, G. (2004). Two-stage thermophilic anaerobic–aerobic digestion of waste-activatedsludge. *Environ. Eng. Sci. 21*, 617–626.

Rosal, R., Rodríguez, A., Perdigón-Melón, J., Petre, A., García-Calvo, E., Gómez, M., et al. (2010). Occurrence of emerging pollutants in urban wastewater and their removal through biological treatment followed by ozonation. *Water Res., 44 (2)*, 578-588.

Rosario-Ortiz, F., Wert, E., and Snyder, S. (2010). Evaluation of UV/H_2O_2 treatment for the oxidation of pharmaceuticals in wastewater. *Water Res., 44 (5)*, 1440-1448.

Ruiz, I., Veiga, M. C., Santiago, P. d., and Blazquez, R. (1997). Treatment of slaughterhouse wastewater in a UASB reactor and an anaerobic filter. *Bioresource Technology 60 (3)*, 251-258.

Sachon (1982). Traitement des eaux résiduaires des abattoirs de bétail. *Proceedings of the International Symposium on Food Industries and The Environment*, (pp. 293-305). Budapest, Hungary.

Sachon, G. (1986). Les eaux résiduaires des abattoirs de bétail. Gestion et traitement. *Tribune Cebedeau 515*, 27-45.

Salminen, E., and Rintala, J. (2002). Anaerobic digestion of organic solid poultry slaughterhouse waste – a review. *Bioresour. Technol. 83*, 13–26.

Sangodoyin, A., and Agbawhe, O. (1992). Environmental study on surface and groundwater pollutants from abattoir effluents. *Bioresour. Technol. 41*, 193-200.

Sarria, V., Deront, M., Peringer, P., and Pulgarin, C. (2003). Degradation of a biorecalcitrant dye precursor present in industrial wastewaters by a new integrated iron(III) photoassisted-biological treatment. *Appl. Catal. B-Environ. 40*, 231-246.

Sarria, V., Parra, S., Invernizzi, M., Péringer, P., and Pulgarin, C. (2001). Photochemical-biological treatment of a real industrial biorecalcitrant wastewater containing 5-amino-6-methyl-2-benzimidazolone. *Water Sci. Technol., 44 (5)*, 93-101.

Sarria, V., Péringer, P., Cáceres, J., Blanco, J., Malato, S., and Pulgarín, C. (2009). Solar degradation of 5-amino-6-methyl-2-benzimidazolone by TiO2 and iron (III) catalyst with H2O2. *Sol. Energy 29*, 853–860.

Sawyer, C., McCarthy, P., and Martin, G. (2002). *Chemistry for Environmental Engineering and Science (5th ed.).* New York, NY: McGraw-Hill Science.

Sayed, S., and De Zeeuw, W. (1988). The performance of a continuously operated flocculent sludge UASB reactor with slaughterhouse wastewater. *Biol. Waste., 24 (3)*, 199-212.

Sayed, S., van Campen, L., and Lettinga, G. (1987). Anaerobic treatment of slaughterhouse waste using a granular sludge UASB reactor. *Biol. Waste., 21 (1)*, 11-28.

Sayed, S., Zanden, J. v., Wijffels, R., and Lettinga, G. (1988). Anaerobic degradation of the various fractions of slaughterhouse wastewater. *Biological Wastes 23*, 117-142.

Schaar, H., Clara, M., Gans, O., and Kreuzinger, N. (2010). Micropollutant removal during biological wastewater treatment and a subsequent ozonation step. *Environ. Pollut., 158 (5)*, 1399-1404.

Sehested, K., Rasmussen, O., and Fricke, H. (1968). Rate constants of OH with HO2, O2-, and H2O2+ from hydrogen peroxide formation in pulse-irradiated oxygenated water. *J. Phys. Chem., 72 (2),* 626-631.

Seif, H., and Moursy, A. (2001). Treatment of Slaughterhouse Wastes. *Sixth International Water Technology Conference* (pp. 269-275). Alexandria, Egypt: IWTC.

Setiadi, T., Husaini, and Djajadiningrat, A. (1996). Palm oil mill effluent treatment by anaerobic baffled reactors: Recycle effects and biokinetic parameters. *Water Sci. Technol., 34 (11 pt 7),* 59-66.

Shannon, M., Bohn, P., Elimelech, M., Georgiadis, J., Mariñas, B., Mayes, et al. (2008). Science and technology for water purification in the coming decades. *Nature 452,* 301–310.

Shemer, H., Kunukcu, Y., and Linden, K. (2006). Degradation of the pharmaceutical Metronidazole via UV, Fenton and photo-Fenton processes. *Chemosphere, 63 (2),* 269-276.

Shen, C., and Guiot, S. (1996). Long-term impact of dissolved O2 on the activity of anaerobic granules. *Biotechnol. Bioeng. 49,* 611–620.

Shu, H. (2006). Degradation of dyehouse effluent containing C.I. Direct Blue 199 by processes of ozonation, UV/H_2O_2 and in sequence of ozonation with UV/H_2O_2. *J. Hazard. Mater. 133,* 92–98.

Sigge, G., Britz, T., Fourie, P., Barnardt, C., and Strydom, R. (2002). Combining UASB technology and advanced oxidation processes (AOP's) to treat food processing wastewaters. *Water Sci. Technol. 45,* 329–334.

Sirianuntapiboon, S., and Manoonpong, K. (2001). Application of granular activated carbon-sequencing batch reactor (GAC-SBR) system for treating wastewater from slaughterhouse. *Thammasat Int. J. Sci. Technol. 6 (1),* 16-25.

Sirtori, C., Zapata, A., Oller, I., Gernjak, W., Agüera, A., and Malato, S. (2009). Solar photo-fenton as finishing step for biological treatment of a pharmaceutical wastewater. *Environ. Sci. Technol., 43 (4),* 1185-1191.

Sklyar, V., Epov, A., Gladchenko, M., Danilovich, D., and Kalyuzhnyi, S. (2003). Combined biologic (anaerobic–aerobic) and chemical treatment of starch industry wastewater. *Appl. Biochem. Biotechnol. 109,* 253–262.

Sperling, M. v., Freire, V., and Chernicharo, C. d. (2001). Performance evaluation of a UASB-activated sludge system treating municipal wastewater. *Water Sci. Technol. 43,* 323–328.

Sponza, and Demirden, P. (2007). Treatability of sulfamerazine in sequential upflow anaerobic sludge blanket reactor (UASB)/completely stirred tank reactor (CSTR) processes. *Sep. Purif. Technol. 56*, 108–117.

Sroka, E., Kamiński, W., and Bohdziewicz, J. (2004). Biological treatment of meat industry wastewater. *Desalination, 162 (1-3)*, 85-91.

Staehelin, J., Bühler, R., and Hoigné, J. (1984). Ozone decomposition in water studied by pulse radiolysis. 2. OH and HO4 as chain intermediates. *J. Phys. Chem., 88 (24)*, 5999-6004.

Steber, J., and Wierich, P. (1986). Properties of hydroxyethano diphosphonate affecting environmental fate: degradability, sludge adsorption, mobility in soils, and bioconcentration. *Chemosphere 15*, 929–945.

Stefan, M., Hoy, A., and Bolton, J. (1996). Kinetics and mechanism of the degradation and mineralization of acetone in dilute aqueous solution sensitized by the UV photolysis of hydrogen peroxide. *Environ. Sci. Technol. 30*, 2382–2390.

Stephenson, T., and Lester, J. N. (1986). Evaluation of startup and operation of four anaerobic processes treating a synthetic meat waste. *Biotechnol. Bioeng., 28 (3)*, 372-380.

Supaka, N., Juntongjin, K., Damronglerd, S., Delia, M., and Strehaiano, P. (2004). Microbial decolorization of reactive azo dyes in a sequential anaerobic–aerobic system. *Chem. Eng. J. 99*, 169–176.

Szpyrkowicz, L., Kaul, S., Neti, R., and Satyanarayan, S. (2005). Influence of anode material on electrochemical oxidation for the treatment of tannery wastewater. *Water Res., 39 (8)*, 1601-1613.

Tabrizi, G., and Mehrvar, M. (2004). Integration of advanced oxidation technologies and biological processes: recent developments, trends, and advances. *J. Environ. Sci. Health Part A 39*, 3029–3081.

Tabrizi, G., and Mehrvar, M. (2006). Pilot-plant study for the photochemical treatment of aqueous linear alkyl benzene sulfonate. *Sep. Purif. Technol. 49*, 115–121.

Tanaka, Hisanaga, J., and Harada, K. (1989a). Efficient photocatalytic degradation of chloral hydrate in aqueous semiconductor suspensions. Journal of Photochemistry and Photobiology A. *Chem. 48*, 155-159.

Tanaka, K., Hisanaga, J., and Harada, K. (1989b). Photocatalytic degradation of organohalide compounds in semiconductor suspensions with added hydrogen peroxide. *N. J. Chem. 13*, 5-7.

Tarr, M. (2003). *Chemical Degradation Methods for Wastes and Pollutants: Environmental and Industrial Applications.* New York, NY: Marcel Dekker.

Tartakovsky, B., Manuel, M., and Guiot, S. (2005). Degradation of trichloroethylene in a coupled anaerobic–aerobic bioreactor: Modeling and experiment. *Biochem. Eng. J. 26*, 72–81.

Tartakovsky, Michotte, A., Cadieux, J., Lau, P., Hawari, J., and Guiot, S. (2001). Degradation of Aroclor 1242 in a single-stage coupled anaerobic/aerobic bioreactor. *Water Res. 35*, 4323–4330.

Tchobanoglous, G., Burton, F., and Stensel, H. (2003). *Wastewater Engineering: Treatment and Reuse (4th ed.)*. New York, NY: McGraw Hill.

Tezel, U., Guven, E., Erguder, T., and Demirer, G. (2001). Sequential (anaerobic/aerobic) biological treatment of dalaman SEKA Pulp and Paper Industry effluent. *Waste Manage. 21*, 717–724.

Toldrá, F., Flors, A., Lequerica, J., and Vallés, S. (1987). Fluidized bed anaerobic biodegradation of food industry wastewaters. *Biol. Waste., 21 (1)*, 55-61.

Toor, R., and Mohseni, M. (2007). UV-H2O2 based AOP and its integration with biological activated carbon treatment for DBP reduction in drinking water. *Chemosphere 66*, 2087–2095.

Torkian, A., Eqbali, A., and Hashemian, S. (2003). The effect of organic loading rate on the performance of UASB reactor treating slaughterhouse effluent. *Resour. Conserv. and Recy., 40 (1)*, 1-11.

Torrades, F., Pérez, M., Mansilla, H., and Peral, J. (2003). Experimental design of Fenton and photo-Fenton reactions for the treatment of cellulose bleaching effluents. *Chemosphere, 53 (10)*, 1211-1220.

Torres, R., Sarria, V., Torres, W., Peringer, P., and Pulgarin, C. (2003). Electrochemical treatment of industrial wastewater containing 5-amino-6-methyl-2-benzimidazolone: Toward an electrochemical-biological coupling. *Water Res., 37 (13)*, 3118-3124.

Treguer, R., Tatin, R., Couvert, A., Wolbert, D., and Tazi-Pain, A. (2010). Ozonation effect on natural organic matter adsorption and biodegradation - Application to a membrane bioreactor containing activated carbon for drinking water production. *Water Res., 44 (3)*, 781-788.

Trgovcich, B., Kirsch, E., and Grady, C. (1983). Characteristics of activated sludge effluents before and after breakpoint chlorination. *Res. J. Water Pollut. C. 55*, 966–976.

Tritt, W. (1992). The anaerobic treatment of slaughterhouse wastewater in fixed-bed reactors. *Bioresource Technol., 41 (3)* , 201-207.

Tritt, W. P., and Schuchardt, F. (1992). Materials flow and possibilities of treating liquid and solid wastes from slaughterhouses in Germany. A review. *Bioresource Technology 41*, 235-245.

UN FAO. (2010). *Food Outlook: Meat and meat products.* Rome, Italy: Food and Agriculture Organization of the United Nations.

US EPA. (2004). *Effluent Limitations Guidelines and New Source Performance Standards for the Meat and Poultry Products Point Source Category.* Environmental Protection Agency (EPA): Federal Register Vol. 69, No. 173.

USACE. (2004, June). *St. Clair River and Lake St. Clair Comprehensive Management Plan - Chapter 3: Environmental Health of the Watershed.* Retrieved January 30, 2012, from US Army Corps of Engineers Detroit District: http://www.lre.usace.army.mil/_kd/Items/actions.cfm?action=Show&item_id=4312&destination=ShowItem

US-EPA. (2002). *Environmental assessment of proposed effluent limitations guidelines and standards for the meat and poultry products industry point source.* Washington, DC: US Environmental Protection Agency.

Uyanik, S. (2003). A novel anaerobic reactor: Split Fed Anaerobic Baffled Reactor (SFABR). *Turk. J. Eng. Environ.Sci., 27 (5)*, 339-345.

Uyanik, S., Sallis, P., and Anderson, G. (2002). The effect of polymer addition on granulation in an anaerobic baffled reactor (ABR). Part I: Process performance. *Water Res., 36 (4)*, 933-943.

Van Lier, J., Tilche, A., Ahring, B., Macarie, H., Moletta, R., Dohanyos, M., et al. (2001). New perspectives in anaerobic digestion. *Water Sci. Technol. 43*, 1-18.

Venhuis, S., and Mehrvar, M. (2005). Photolytic treatment of aqueous linear alkyl benzene sulfonate. *J. Enviro. Sci. Health Part A 40*, 1731–1739.

Vera, M., Aspe, E., Marti, M., and Roeckel, M. (1999). Optimization of a sequential anaerobic–aerobic treatment of a saline fishing effluent. *Process Saf. Environ. Prot. 77*, 275–290.

Verheijen, L., Wiersema, D., and Pol, L. H. (1996). *Management of Waste from Animal Product Processing.* Retrieved December 10, 2010, from Food and Agriculture Organization of the United Nations - FAO Corporate Document Repository - J. De Wit International Agriculture Centre: http://www.fao.org/WAIRDOCS/LEAD/X6114E/X6114E00.HTM

Vossoughi, M., Shakeri, M., and Alemzadeh, I. (2003). Performance of anaerobic baffled reactor treating synthetic wastewater influenced by decreasing COD/SO4 ratios. *Chem. Eng. Process., 42 (10)*, 811-816.

Walter, R., Shermah, R., and Downing, D. (1974). Reduction in Oxygen demand of abattoir effluent by Precipitation with metal. *Journal of Agricultural and Food Chemistry 22*, 1097-1099.

Wang, Hung, and Shammas. (2006). *Advanced Physicochemical Treatment Process: Volume 4 (Handbook of Environmental Engineering).* Totowa, NJ: Humana Press.

Wang, L. (2005). *Waste Treatment in the Process Industries.* Boca Raton, FL: CRC Press.

Wang, L., Hung, Y., and Shammas, N. (2010). *Handbook of Advanced Industrial and Hazardous Wastes Treatment.* Boca Raton, FL: CRC Press.

Wang, R., Wang, Y., Ma, G., He, Y., and Zhao, Y. (2009a). Efficiency of porous burnt-coke carrier on treatment of potato starch wastewater with an anaerobic–aerobic bioreactor. *Chem. Eng. J. 148*, 35–40.

Wang, X.-J., Song, Y., and Mai, J.-S. (2008). Combined Fenton oxidation and aerobic biological processes for treating a surfactant wastewater containing abundant sulfate. *J. Hazard. Mater., 160 (2-3)*, 344-348.

Wang, Y. (1992). Effect of chemical oxidation on anaerobic biodegradation of model phenolic compounds. *Water Environ. Res. 64*, 268–273.

Wang, Y., and Hong, C. (1999). Effect of hydrogen peroxide, periodate and persulfate on photocatalysis of 2 chlorobiphenyl in aqueous TiO2 suspensions. *Water Res. 33*, 2031-2036.

Wang, Z.-P., Huang, L.-Z., Tao, T., Fu, S., Zuo, J., and Lv, B. (2009b). Treatment of landfill leachate by combined photooxidation and biological anaerobic-aerobic method. *3rd International Conference on Bioinformatics and Biomedical Engineering, iCBBE 2009, art. no. 5163709*, 1-4.

Ward, B. (1996). Nitrification and denitrification: Probing the nitrogen cycle in aquatic environments. *Microb. Ecol., 32 (3)*, 247-261.

World Bank. (1999). *Pollution Prevention and abatement handbook toward cleaner production.* Washington, DC: The International Bank for Reconstruction and Development.

World Bank Group. (2007). *Environmental, Health, and Safety Guidelines for Sugar Manufacturing.* Retrieved December 10, 2010, from International Finance Corporation: http://www.ifc.org/ifcext/enviro.nsf/AttachmentsByTitle/gui_EHSGuidelines2007_SugarManufacturing/$FILE/Final+-+Sugar+Manufacturing.pdf

Wu, P., and Mittal, G. (2011). Characterization of provincially inspected slaughterhouse wastewater in Ontario, Canada. *Can. Biosyst. Eng., 53*, 6.9-6.18.

Yan, M., Wang, D., Ma, X., Ni, J., and Zhang, H. (2010). THMs precursor removal by an integrated process of ozonation and biological granular activated carbon for typical Northern China water. *Sep. Purif. Technol., 72 (3)*, 263-268.

Yang, Z., and Zhou, S. (2008). The biological treatment of landfill leachate using a simultaneous aerobic and anaerobic (SAA) bio-reactor system. *Chemosphere 72*, 1751–1756.

Yeoh, B. (1995). Anaerobic treatment of industrial wastewaters in Malaysia. *Post Conference Seminar on Industrial Wastewater Management.* Kuala Lumpur, Malaysia.

Yu, J., Chen, H., Ji, M., and Yue, P. (2000). Distribution and change of microbial activity in combined UASB and AFB reactors for wastewater treatment. *Bioprocess Eng. 22*, 315–322.

Zeng, Y., Hong, P., and Wavrek, D. (2000). Integrated chemical-biological treatment of benzo[a]pyrene. *Environ. Sci. Technol., 34 (5)*, 854-862.

Zhang, D., Lu, P., Long, T., and Verstraete, W. (2005). The integration of methanogensis with simultaneous nitrification and denitrification in a membrane bioreactor. *Process Biochem. 40*, 541–547.

Zhang, Y., Love, N., and Edwards, M. (2009). Nitrification in drinking water systems. *Crit. Rev. Environ. Sci. Technol., 39 (3)*, 153-208.

Zhang, Y., Yan, L., Qiao, X., Chi, L., Niu, X., Mei, Z., et al. (2008). Integration of biological method and membrane technology in treating palm oil mill effluent. *J. Environ. Sci. 20*, 558–564.

Zhou, H., and Smith, D. (2002). Advanced technologies in water and wastewater treatment. *J. Environ. Eng. Sci. 1*, 247–264.

Zhou, P., Su, C., Li, B., and Qian, Y. (2006). Treatment of high-strength pharmaceutical wastewater and removal of antibiotics in anaerobic and aerobic biological treatment processes. *J. Environ. Eng., 132 (1)*, 129-136.

Zumft, W. (1997). Cell biology and molecular basis of denitrification? *Microbiol. Mol. Biol. Rev., 61 (4)*, 533-616.