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Combined anaerobic baffled reactor and UV/ H₂O₂ process for the treatment of synthetic slaughterhouse wastewater

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COMBINED ANAEROBIC BAFFLED REACTOR AND UV/H₂O₂
PROCESS FOR THE TREATMENT OF SYNTHETIC
SLAUGHTERHOUSE WASTEWATER

by

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A thesis

presented to Ryerson University

in partial fulfillment of the requirement for the degree of

Master of Applied Science

in the Program of

Environmental Applied Science and Management

Toronto, Ontario, Canada, 2009

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ABSTRACT

COMBINED ANAEROBIC BAFFLED REACTOR AND UV/H₂O₂ PROCESS FOR THE TREATMENT OF SYNTHETIC SLAUGHTERHOUSE WASTEWATER

Weihua Cao

Master of Applied Science

Environmental Applied Science and Management

Ryerson University, Toronto, 2009

A laboratory scale for the combined processes of a biological anaerobic baffled reactor (ABR) and a UV/hydrogen peroxide (H₂O₂) was used to investigate the treatment of a synthetic slaughterhouse wastewater with various influent concentrations and various hydraulic retention times (HRT) at room temperature in this study. The results showed that the removal efficiencies of total organic carbon (TOC), chemical oxygen demand (COD), and 5-day carbonaceous biochemical oxygen demand (CBOD₅) of the wastewater with an influent concentration of 973 mgTOC/L and a HRT of 3.8 days reached 89.9, 97.7, and 96.6%, respectively, in the ABR process, whilst the removal efficiency of TOC in the UV/H₂O₂ process reached 50.8% at a HRT of 3.6 h and a H₂O₂ dosage of 1371 mgH₂O₂/L, leading to 95.0% of overall TOC removal of the combined processes. For comparison, the removal efficiencies of TOC, COD, and CBOD₅ of the synthetic wastewater with an influent concentration of 158 mgTOC/L reached 64.9, 81.9, and 84.3%, respectively, at a HRT of 2.5 h and a H₂O₂ dosage of 1371 mgH₂O₂/L in UV/H₂O₂ process alone. An optimum value of hydrogen peroxide was found to be 3.5 (mgH₂O₂/L)/(mgTOC_{in}/L.h).

After the ABR treatment, the ratio of CBOD₅/COD of the untreated wastewater changed from 0.4 to 0.6 and 0.5 to 0.2, and the ratio of COD/TOC of the wastewater decreased from 2.4 to 0.5 and 2.2 to 2.0, at the HRT of 3.8 and 0.9 *days*, respectively, indicating that the biodegradability of the wastewater was enhanced at a longer HRT in the ABR process. After the UV/H₂O₂ process treatment, the ratios of CBOD₅/COD of the untreated and the ABR treated wastewater increased from 0.4 to 0.6 and 0.3 to 0.5, and the ratios of COD/TOC of the wastewaters decreased from 2.3 to 0.6 and 1.8 to 0.9, respectively, at the HRT of 2.5 *h*, indicating that the UV/H₂O₂ process had ability to enhance the biodegradability of the wastewater.

A kinetic model for the ABR process was obtained and used to evaluate the experimental findings. The parameters of the kinetic model for the ABR process were determined to be 3.1×10^{-2} for refractory coefficient, 0.4 for kinetic coefficient, 2.0 *mg/L* for half-saturation constant for hydrolyzed substrate, and 1.9 *day*⁻¹ for the maximum specific growth rate of organism, respectively.

The optimum HRT and the minimum total electricity cost were determined to be 78.9 *h* and \$11.45 /*kg* of TOC removed for the ABR process, with 1000 *mg*TOC/*L* of the wastewater influent concentration, leading to 100.0 *mg*TOC/*L* of the effluent concentration which met the disposal level in Canada.

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NOMENCLATURE

A	kinetic coefficient
A_L	local volumetric rate of energy absorption, $(mol\ photon)/(m^3.s)$
a	pipe cross-sectional area, m^2
a_i	specific biofilm surface area, m^{-1}
b	microorganism decay rate, day^{-1}
B	constant bacterial growth parameter
B_1	DO of seed control before incubation, mg/L
B_2	DO of seed control after incubation, mg/L
$C_{H_2O_2}$	H_2O_2 concentration in wastewater, mg/L
C_i	concentration of organic compound i , M
$CBOD_{5,in}$	$CBOD_5$ concentration of influent wastewater sample, mg/L
$CBOD_{5,out}$	$CBOD_5$ concentration of effluent wastewater sample, mg/L
COD_{in}	COD concentration of influent wastewater sample, mg/L
COD_{out}	COD concentration of effluent wastewater sample, mg/L
D	density of commercial H_2O_2 solution, g/L
D_1	DO of a diluted sample immediately after preparation, mg/L
D_2	DO of a diluted sample after 5 days incubation at $20^\circ C$, mg/L
D_{AB}	diffusivity of organic compound in aqueous solution, m^2/s
f	ratio of the volume of seed solution in GGA test to the volume of seed solution in seed control
F	representative of a non-linear least square function
$F_{ABRElec}$	electricity cost of ABR process per unit mass of TOC removed, $\$/kg$
F_{Elec}	total cost of electricity per unit mass of TOC removed, $\$/kg$

G	methane volume accumulated at a given time, L
G_m	maximum methane volume accumulated at an infinite digestion time, L
i	values of 1 to 5 compartments
k	rate constant, h^{-1}
k_h	hydrolyzed substrate transport rate coefficient, day^{-1}
k_i	the first order rate coefficient of substrate in the i^{th} compartment, $L/(g \cdot day)$
k_{RH}	the second-order rate constant, $L/mg \cdot h$
k_{S_n}	the second-order rate constant, $L/mg \cdot h$
K_h	substrate hydrolysis rate coefficient, day^{-1}
K_m	concentration of substrate when the rate of substrate utilization is half of maximum rate, g/L
K_{obs}	specific rate constant, day^{-1}
K_c	substrate concentration when the growth rate constant is half of maximum rate constant, $mass/volume$
K_s	half-saturation constant for substrate, g/L
L	characteristic length that the flow is going through or around, m
m	maintenance constant, day^{-1}
p	power rating for system, W
p_{ABR}	power rating of ABR process, W
P	decimal volumetric fraction of sample used (dimensionless)
P_m	density of bacterial population, mM/L
P_{power}	price of power, $$/kWh$
Q	wastewater flowrate, L/min or m^3/s
Q_{H2O2}	flowrate of H_2O_2 solution, L/min

Q_i	specific flow rate of compartment i , /s
q	radiant energy flux, (mol photons)/(m ² .s)
q_o	radiant energy flux at the outer surface of UV lamp, (mol photons)/(m ² .s)
q_i	variable reaction order (dimensionless)
r	radial position, m
r_r	recycle rate (dimensionless)
R	refractory coefficient (dimensionless)
R_c	variable-order reaction coefficient
Re	Reynolds number (dimensionless)
R_i	inner reactor radius, m
$R_{rxn,i}$	reaction rate of organic compound i , M/s
$R_{rxn,1}$	the reaction rate of $\cdot OH$, $mg/L.h$
$R_{rxn,2}$	the reaction rate of $\cdot OH$ with RH, $mg/L.h$;
$R_{rxn,3n}$	the reaction rate of $\cdot OH$ with a scavenger S_n , where $n = a, b, \dots, n$, $mg/L.h$
R_s	specific growth rate, h^{-1}
S	substrate concentration, g/L
S_0	substrate influent concentration, g/L
S_c	concentration of limiting substrate, mM
S_e	substrate effluent concentration of ABR, g/L
S_h	substrate hydrolysis rate coefficient, day^{-1}
S_i	substrate concentration in the i^{th} compartment, g/L
S_{i-1}	substrate concentration in the $(i-1)^{th}$ compartment i , g/L
S_r	refractory substrate concentration in influent
S_n	a scavenger for the $\cdot OH$, where $n = a, b, \dots, n$
S_{T0}	total substrate concentration in influent, mg/L

S_T	total substrate concentration in effluent, mg/L
S_u	concentration of hydrolyzed substrate entering the microorganisms, mg/L
t	retention time, h
t_{ABR}	retention time of ABR process, h
t_d	digestion time, day
t_{UV}	retention time of UV/H ₂ O ₂ process, h
TOC_{in}	TOC concentration of influent wastewater sample, mg/L
TOC_{out}	TOC concentration of effluent wastewater sample, mg/L
u	mean fluid velocity, m/s
u_m	constant bacterial growth parameter (dimensionless)
v_r	velocities in r -directions, m/s
v_θ	velocities in θ -directions, m/s
v_z	velocities in z -directions, m/s
V	volume of sample, L
V_{ABR}	volume of ABR reactor, L
V_{DWater}	volume of distilled water, L
V_i	volume of the i^{th} compartment, L
V_{H2O2}	volume of commercial H ₂ O ₂ solution, L
V_{max}	maximum rate of substrate utilization at high substrate concentration, $/day$
V_{UV}	volume of UV photoreactor, L
X	concentration of microorganism, g/L
X_i	biomass concentration of the i^{th} compartment, g/L
Y	yield coefficient (dimensionless)
Y_b	biomass yield coefficient, $mg\ cell/mg\ substrate$
W_l	sum of weights of the dried filter paper, dish and dried solids of sample, mg

W_2	weight of dried filter paper, <i>mg</i>
W_3	weight of dried dish, <i>mg</i>
W_4	sum of weights of solids of sample and dish after burning, <i>mg</i>

Greek Letters

ε	molar absorptivity, $(M.m)^{-1}$
μ	growth rate constant used in Equation (2.6), day^{-1} ; and dynamic viscosity of the fluid used in Equation (3.8), $kg/m.s$
μ_m	maximum value of organism growth rate constant, day^{-1}
μ_s	solution extinction coefficient at 254 <i>nm</i> , m^{-1}
μ_w	extinction coefficient of water at 254 <i>nm</i> , m^{-1}
ζ	a constant that depends on an AOP process, $mg/h.W$
ρ	density of the fluid, kg/m^3
φ	quantum yield constant, $(mol\ of\ H_2O_2\ or\ target\ compound)/photon$

Abbreviation

ABR	anaerobic baffled reactor
AF	anaerobic filter
AOP	advanced oxidation process
BAT	Best available technology economically achievable
BCT	Best control technology for conventional pollutants
BOD	biochemical oxygen demand
BOD ₅	biochemical oxygen demand in 5 days

BPT	best practicable control technology currently available
CBOD ₅	carbonaceous biochemical oxygen demand in 5 days
CFC	chlorofluorocarbons
COD	chemical oxygen demand
CSTR	continuous stirred tank reactor
DAF	dissolved air flotation
DO	dissolved oxygen
EHS	Environmental Health and Safety
EPA	Environmental Protection Agency
GGA	Glucose-glutamic acid
HRT	hydraulic retention time
IFC	International Finance Corporation
LVREA	local volumetric rate of energy absorption
MPN	most probable number
MPP	Meat and Poultry Products
NSPS	New source performance standards
O&G	oil and grease
O&M	operating and maintenance
OLR	organic loading rate
RH	target compound
SCF	seed correction factor
SCOD	soluble chemical oxygen demand
SS	suspended solids
TBOD	total biochemical oxygen demand
TKN	total kjeldahl nitrogen

TN	total nitrogen
TOC	total organic carbon
TP	total phosphorus
TSP	international Time Series Processor
TSS	total suspended solid
UASB	upflow anaerobic sludge blanket
UNEP/MAP	United Nations Environment Programme/Mediterranean Action Plan
VFA	volatile fatty acid
VSS	volatile suspended solid

CHAPTER 1

INTRODUCTION

With the rapid development of various industries, the protection and preservation of natural resources has become a crucial challenge for sustainable environmental development of the whole society. Nowadays, wastewater treatment becomes one of the most significant issues. Although governments require wastewater discharge from industries to be controlled before releasing it to the environment, the treatment performance of industrial wastewater should be enhanced.

Wastewater treatment technologies including physical, chemical and biological methods are classified as three main categories: primary, secondary, and tertiary treatments. They are widely used to remove contaminants from wastewater to achieve different levels of contaminant removal. It has been identified that screen, oil and grease removal units, dissolved air floatation, adsorption, stripping, coagulation, flow equalization, filtration, disinfection, biological treatment including any combination of aerobic lagoon, anaerobic lagoon, facultative lagoon, activated sludge process, and/or other biological treatment processes are common wastewater treatment methods for industrial wastewater treatment (US EPA, 2002). Specially, biological treatment technologies have been frequently used to reduce biodegradable organic pollutants in municipal and industrial wastewater such as slaughterhouse wastewater.

Slaughterhouse wastewater is a typical organic wastewater and its amount has largely

risen in many countries due to the increase in water consumption in the processes of dairies, slaughterhouses and meat processing in order to meet the increasing demands of meat. The term “slaughterhouse” refers to abattoir and any place where cattle, sheep, swine, or other animals are killed for subsequent use as food for human consumption (*N.B. Reg. 88-200*). Slaughterhouse wastewater may pollute receiving water resources due to its high levels of biochemical oxygen demand (BOD), chemical oxygen demand (COD), and suspended solids (SS), and may affect human health due to its high levels of pathogenic bacteria and parasites. Therefore, purifying slaughterhouse wastewater is a necessary task before releasing it to the receiving waters.

Many treatment technologies from physical, physico-chemical, and electrochemical to biological technologies for slaughterhouse wastewater have been investigated. Previous research studies have pointed out the treatment ability of biological anaerobic treatment technologies for slaughterhouse wastewater but still there are some problems such as high concentration of organic matters and pathogens in the effluent of the wastewater.

In this study, a synthetic slaughterhouse wastewater was prepared as a model sample to conduct the experiments. A biological anaerobic treatment technology (anaerobic baffled reactor, ABR), an advanced oxidation process (UV/H₂O₂ process), and their combination were designed for the treatment of the synthetic slaughterhouse wastewater.

OBJECTIVES

Combined processes of ABR and UV/H₂O₂ were investigated based on the advantages of ABR and UV/H₂O₂ for the synthetic slaughterhouse wastewater in this study. Therefore, the

objectives of this study are:

- (1) to identify the performance and the treatment ability of the ABR process, the UV/H₂O₂ process, and their combination through the evaluation of the removal efficiencies of total organic carbon (TOC), chemical oxygen demand (COD), 5-day carbonaceous biochemical oxygen demand (CBOD₅), and total nitrogen (TN),
- (2) to prove the improvement of treatment ability of the combined processes for the wastewater,
- (3) to compare the biodegradability of the synthetic slaughterhouse wastewater before and after the ABR and the UV/H₂O₂ processes,
- (4) to investigate the modeling of the ABR process, and
- (5) further to investigate the optimization of the total hydraulic retention time and the electricity cost the ABR.

CHAPTER 2

LITERATURE REVIEW

2.1 SLAUGHTERHOUSE WASTEWATER

This section discussed the general information on slaughterhouse wastewater including its characteristics and by-products, environmental impacts and health effects, and regulations and guidelines of its disposal. The treatment technologies for meat and poultry processing and some studies for the treatment of slaughterhouse wastewater are summarized in this section.

2.1.1 Characteristics and By-products

Slaughterhouse wastewater is a typical industrial wastewater with high levels of loading in organics, inorganics and suspended solids (SS), including contents of lard, fats, proteins, salt, nitrogen, phosphorous, pathogenic and non-pathogenic viruses and bacteria, parasite eggs, urine, loose meat, grease, hair, feathers, flesh, manure, particles, grit, and undigested food (Bull *et al.*, 1982; Jian and Zhang, 1999). Detergents and disinfectants, such as acid, alkaline, neutral compounds, disinfectants, and liquid paraffin, may enter the wastewater stream during facility-cleaning activities. It has been reported that the concentrations of biochemical oxygen demand (BOD), chemical oxygen demand (COD), and suspended solid (SS) due to the presence of blood, tallow, and mucosa can reach to 151,000 to 200,000, 375,000, and 800 mg/L or higher, respectively (Haan *et al.*, 1996; Tritt and Schuchardt, 1992;

The Word Bank, 1998). The ranges of total COD, total Kjeldahl nitrogen (TKN) and SS were within 2,333-8,627, 90-593, and 736-2,099 *mg/L*, respectively, for untreated wastewater from six hog slaughterhouses in Quebec and Ontario, Canada in 1995 and 1996 (Massé and Masse, 2000a; Mittal, 2004). A potential pollutant load of 1,710,000 tons of BOD per year is produced by slaughterhouse industries just from the blood alone. This is equivalent to the organic pollutants from wastewater generated by 11,000,000 people (Al-Mutairi *et al.*, 2003). In some cases, offensive odors may occur (The Word Bank, 1998). The general characteristics of slaughterhouse wastewater based on a survey in 1999 are shown in Table 2.1 (Núñez *et al.*, 1999; UNEP/MAP, 2004).

Table 2.1: General characteristics of slaughterhouse wastewater (Nunez *et al.*, 1999; UNEP/MAP, 2004).

Parameter	Concentration		
	High	Medium	Low
pH	7.5	6.8	6.5
Total COD (<i>mg/L</i>)	4,200	2,510	1,450
Soluble COD (<i>mg/L</i>)	2,100	1,510	720
Total BOD ₅ (<i>mg/L</i>)	2,410	1,410	1,100
Total Suspended Solid (TSS) (<i>mg/L</i>)	841	541	381
Fats (<i>mg/L</i>)	290	151	46
Total Nitrogen (TN) (<i>mg/L</i>)	200	N/A	100
Total Phosphorous (<i>mg/L</i>)	20	N/A	10

Slaughterhouse wastes contain useful by-products (UNEP/MAP, 2004). For examples, slaughterhouse sludge containing crude protein, biogenic amines and ammonia, and essential amino acids has potential use for pig and poultry feeding (Gariépy *et al.*, 1989; Hann *et al.*,

1996; Fransen *et al.*, 1995; Ponsano *et al.*, 2003); and phosphorus in anaerobically digested poultry manure has been used as feed supplement for chicks without toxicity or negative effects (Shih, 1993).

Anaerobically digested slaughterhouse solids containing rich nutrients can be recycled and reused as an agricultural fertilizer (Salminen *et al.*, 2001; Marchaim *et al.*, 1991; Shih, 1993; Hann *et al.*, 1996). The slurry of anaerobic digestion containing rich ammonia mineralized from organic nitrogen in slaughterhouse wastewater can be used on farmlands (Salminen and Rintala, 2002). Slaughterhouse wastewater can be used for irrigation and fish or algae production (Hann *et al.*, 1996). The biogas generated by anaerobic digestion on-site as a by-product can be used as an energy source such as electricity, heating, or drying (Shih, 1993).

2.1.2 Environmental Impacts and Health Effects

Slaughterhouse industries discharge wastewater containing high concentration of organic matter or toxic compounds, such as chromium, into surface and subsurface water (Torkian *et al.*, 2003; Verheijen *et al.*, 1996). The main environmental impacts of slaughterhouse wastewater discharge into surface water include a reduction of dissolved oxygen in the aquatic layer, eutrophication and oxygen depletion caused by nitrogen and phosphates. The discharge of slaughterhouse wastewater may also cause fish death in ponds, color and smell of water in canals, ditches and ponds, and rich organic matter and algae in lakes and reservoirs. All of these impacts will influence the water ecosystem and lead to a serious decline in water quality. The impacts of slaughterhouse wastewater discharge into the soil and underground water include the pollution of nitrate and chloric anion in underground

water, and the increase of biological pollution from many pathogenic microorganisms in cattle manure, which will persist in the soil forever and reproduce continuously. Consequently, soil and underground water used for drinking and irrigation can be seriously polluted (Fang, 2000).

The most significant environmental impact resulting from slaughtering activities is their wastes emitted such as blood, manure, hair, fat, feathers, muscle, and bones, which may bring high concentrations of BOD, COD and total suspended solids (TSS) to slaughterhouse wastewater and is related to water consumption (UNEP/MAP, 2004). Large quantities of slaughterhouse wastewater are caused by large quantities of water consumption in slaughterhouse for evisceration, cleaning and washing operations. Slaughterhouse wastewater has been classified by the United States Environmental Protection Agency (US EPA) as one of the most harmful wastewaters to the environment (Gariépy *et al.*, 1989).

In addition, pathogenic bacteria, parasites, and viruses generated by slaughtering processes may contribute numerous hazards to human health (Salminen and Rintala, 2002). For instance, countries in Latin American have experienced serious gastrointestinal diseases, such as diarrhea, because of the presence of viruses, bacteria, protozoa, and helminth eggs in slaughterhouse wastewater (Velásquez *et al.*, 2004). After studying the bacteriology, it was determined that the Ikpoba River in Nigeria contained a high heterotrophic bacterial load (6.0×10^4 - 7.0×10^7 cfu/mL) in 1993 due to a continual discharge of untreated slaughterhouse wastewater into the river (Benka-Coker and Ojior, 1995). The heterotrophic bacterial population in the river increased from 10^4 to 10^7 /mL after mixing with slaughterhouse wastewater. Six identified bacterial genera, *Salmonella*, *Escherichia*, *Shigella*, *Klebsiella*, *Streptococcus* and *Staphylococcus*, were found in the river. Total coliforms and *Escherichia*

coli showed high counts of 1.6×10^6 - 2.4×10^6 /mL. The dissolved oxygen (DO) was dropped from 7.2 to about 2.4 mg/L, while SS, BOD₅, nitrate, and phosphate levels were increased appreciably.

The environmental impacts of slaughterhouse wastewater can be significantly reduced by simple technologies such as waste prevention and the use of by-products. For example, dry rendering of offal and cutting down on water consumption can reduce the amount of slaughterhouse wastewater produced. Collecting wastes as solids as far as possible can reduce contaminants concentrations in slaughterhouse wastewater. If the wastewater discharges without any treatment, it would have critical effects on the environment, and might easily lead to environmental pollution and human health risks (Fang, 2000; Polprasert *et al.*, 1992; Nhat, 2006). Therefore, it is necessary for slaughterhouses industries to purify their wastewater before discharging it.

2.1.3 Regulations and Guidelines of Slaughterhouse Wastewater

Regulations and guidelines are essential components in dealing with the environmental impact of slaughterhouse industries. Their roles are to limit or prohibit the use of chromium in tanneries, control the use of chlorofluorocarbons (CFCs) in chilling processes, limit the total BOD output in wastewater, and prescribe odor and gaseous emission control (Haan *et al.*, 1996). If wastewater contains nitrogen contents and nitrification is inhibited during BOD testing, 5-day carbonaceous biochemical oxygen demand (CBOD₅), which is equivalent to BOD, will be reported in place of BOD (APHA *et al.*, 1998). The standard levels recommended for slaughterhouse wastewater discharge in Canada are shown in Table 2.2. The effluent guidelines and maximum levels for meat processing which are indicative of

good international industry practice are shown in Table 2.3. These levels should be achieved without dilution during at least 95% of the plant or unit operation time. Furthermore, these levels are applicable for direct discharge of treated effluents to surface water for general use (IFC, 2007). Under a well designed, well operated and well maintained pollution prevention and control system, the effluent concentration from slaughterhouse processing could be reduced to achieve the guideline levels.

Table 2.2: Recommendations for wastewater disposal from federal facilities in Canada
(Correctional Service Canada, 2003).

Parameters	Water Resources of Disposal	Recommended Disposal Concentration (mg/L) (unless otherwise specified)
Biochemical oxygen demand (BOD ₅)	Freshwater, lakes, slow-flowing streams	5
	Rivers, streams and estuaries	20
	Shoreline	30
Fecal <i>coliform</i>		100/100 mL
Total <i>coliform</i> count		1,000/100 mL
TSS	Freshwater, lakes, slow-flowing streams	5
	Rivers, streams and estuaries	20
	Shoreline	30
pH		6 to 9
Oil and grease		5
Ammonia (NH ₃)		1.0
Nitrates (NO ₃ ⁻ , NO ₂ ⁻ , in N form)		10
Phosphorus (P)		1.0
Sulphur (in S form)		0.5
Temperature	Temperature of discharge cannot change ambient temperature by more than 1°C.	

Table 2.3: Slaughterhouse wastewater disposal effluent levels for meat processing (IFC, 2007; The World Bank, 1998).

Parameters	EHS ¹ Guideline Levels	Maximum Levels
pH	6-9	6-9
BOD ₅ (mg/L)	50	50
COD (mg/L)	250	250
Total nitrogen (NH ₄ ⁺ -N) (mg/L)	10	10
Total phosphorus (mg/L)	2	5
Oil and grease (mg/L)	10	10
Total suspended solids (mg/L)	50	50
Temperature increase (°C)	<3	-
Total coliform bacteria (MPN ² /100 mL)	410	400
Active ingredients / Antibiotics	To be determined on a case specific basis	

Note: 1. Environmental Health and Safety; 2 .MPN = Most Probable Number

2.1.4 Research Studies on Slaughterhouse Wastewater

Table 2.4 summarizes the treatment technologies for slaughterhouse wastewater that have been successfully designed to deal with the health effects and environmental impacts caused by slaughterhouse wastewater.

Physical treatment technologies have been investigated to treat slaughterhouse wastewater. It was reported by Massé and Masse (2000a) that sewer discharge without preliminary treatment was used mostly by smaller slaughterhouses located near municipal wastewater treatment plants. The slaughterhouse wastewater was diluted by domestic wastewater leading to a much lower BOD and inorganic nutrient concentration and, thus, became more amenable to biological treatment. Massé and Masse (2000a) and Bull *et al.* (1982) identified that the land application was very simple, with low costs for slaughterhouse wastewater and had been mainly used by spray irrigation in the USA. Constructed wetlands

Table 2.4: Summary of technologies for MPP¹ facilities (Source: Mittal, 2006).

Category	Regulatory Level	Technology
Simple abattoir	BPT ²	Equalization, dissolved air flotation, secondary biological treatment with nitrification
Complex abattoir	BPT	Equalization, dissolved air flotation, secondary biological treatment with nitrification and denitrification
Low-processing packaging	BAT ³ , NSPS ⁴	Equalization, dissolved air flotation, secondary biological treatment with nitrification and denitrification
High-processing packaging	BAT, NSPS	Equalization, dissolved air flotation, secondary biological treatment with nitrification
Meat cutter	BPT	Equalization, dissolved air flotation, secondary biological treatment with nitrification
Sausage and luncheon meats processor	BPT	Equalization, dissolved air flotation, secondary biological treatment with nitrification and denitrification
Ham processor	BAT, NSPS	Equalization, dissolved air flotation, secondary biological treatment with nitrification and denitrification
Canned meat processor	BAT, NSPS	Equalization, dissolved air flotation, secondary biological treatment with nitrification
Renderer	BPT, BCT ⁵	Equalization, dissolved air flotation, secondary biological treatment with nitrification
Poultry first processing (facilities which slaughter poultries up to 10 million <i>lb/year</i>)	BPT, BCT	Equalization, dissolved air flotation, secondary biological treatment with less efficient nitrification
Poultry further processing (facilities which produce up to 7100 <i>lb/year</i> of product)	BAT, NSPS	Equalization, dissolved air flotation, secondary biological treatment with less efficient nitrification
Poultry first processing (facilities which slaughter up to 10 million <i>lb/year</i>)	BPT, BCT	Equalization, dissolved air flotation, secondary biological treatment with nitrification and denitrification
Poultry further processing (facilities which produce up to 7100 <i>lb/year</i> of product)	BAT, NSPS	Equalization, dissolved air flotation, secondary biological treatment with nitrification and denitrification

Note: ¹MPP – Meat and poultry products

²BPT – Best practicable control technology currently available

³BAT – Best available technology economically achievable

⁴NSPS – New source performance standards

⁵BCT – Best control technology for conventional pollutants

combined with anaerobic lagoons had been applied to treat slaughterhouse wastewater with 91% BOD₅ removal, 89% COD removal, 85% TSS removal, 80% organic nitrogen removal, and effective removal of pathogens and *Coliform* (Gutiérrez-Sarabia *et al.*, 2004). However, 60% phosphorus was stored in sediments using wetland treatment (White *et al.*, 2000).

Physico-chemical treatment technologies have been studied by many investigators for slaughterhouse wastewater treatment. It was reported by Viraraghavan (1988) that peat filtration could remove 66, 65, 94, and 87% BOD, COD, SS, and P, respectively. Ozone's ability to significantly reduce BOD, COD, and TOC in slaughterhouse wastewater was observed by Millamena (1992). Ozone's effectiveness in disinfecting slaughterhouse wastewater was found by Wu and Doan (2005). Dissolved air flotation (DAF) was able to remove large amounts of nutrients with low capital cost (Massé and Masse, 2000a; Johns, 1995). Coagulation combined with flocculation could effectively reduce organic matter (Sanchis *et al.*, 2003; Núñez *et al.*, 1999). The process of DAF-coagulation-flocculation-DAF was used to achieve a high SS removal with good clarification (Al-Mutairi *et al.*, 2004).

Electrochemical treatment technologies have been also studied. It was found by Kobya *et al.* (2006) and Bayramoglu *et al.* (2006) that electrocoagulation could achieve 93% COD removal by using aluminum electrode and 98% oil and grease removal through iron electrode. Manaila *et al.* (2005) observed that polyelectrolytes were very effective and inexpensive to reduce COD, TSS, and fat matter. Electrolytes were found to be able to change 100% sulphide into insoluble precipitates and remove more than 70% COD (Marconato *et al.*, 1998).

Biological treatment is one of the most reliable processes to treat slaughterhouse

wastewater under anaerobic or aerobic conditions to remove COD, BOD and other contaminants. In aerobic digestion, microorganisms degrade organics in the presence of oxygen, while the system generates large quantities of biological sludge (Massé and Masse, 2000a; Rudd, 1985). Aerobic treatment processes are limited by their high energy consumption needed for aeration and high sludge production (Kobya, M.; *et al.* 2006). Anaerobic systems have been demonstrated to be the most suitable wastewater treatment systems for slaughterhouse wastewater (Sayed *et al.*, 1987; Borja *et al.*, 1998; Rajeshwari *et al.*, 2000; Torkian *et al.*, 2003). During anaerobic digestion, organics are degraded by various bacteria into methane and carbon dioxide in the absence of oxygen (Tritt *et al.*, 1992). Table 2.5 summarizes the processes that have been used for the biological treatment of slaughterhouse wastewater.

2.2 ANAEROBIC DIGESTION

Anaerobic digestion is defined as “the biological oxidation of degradable organic sludge by microbes under anaerobic conditions” (Reynolds and Richard, 1996). Anaerobic digestion processes of various configurations have been studied for the treatment of slaughterhouse wastewater. Simple anaerobic systems could reduce BOD by half, while sophisticated anaerobic systems could reduce BOD by 90% or more (Hann *et al.*, 1996). The reduction of soluble and insoluble COD can also reach to a high efficiency with a low production of sludge (only 5 to 20% of that generated by an aerobic system). Anaerobic systems do not require aeration energy and chemical handling to reduce BOD and COD at a high efficiency, and they employ microbes to reduce organic matter in wastewater. In the anaerobic digestion process, about 70% of all the methane produced converts from acetate which comes from volatile fatty acids (VFAs) (McCarty and Mosey, 1991).

Table 2.5: Summary of recent studies on the biological treatment of slaughterhouse wastewater.

Treatment Technology	Initial Concentration (mg/L)	Treatment Efficiency (% Removal)	Advantage	Disadvantage	References
Dissolved air flotation (DAF) – upflow anaerobic sludge blanket (UASB)	BOD ₅ : 600-3900 COD: 1100-7250 SS: 300-2300 TKN: 90-150 Phosphate: 8-15	TCOD: 90% COD: 50% (DAF) Waste strength: about 50% (DAF)	Feasible system; the float and subnatant in a slaughterhouse wastewater rendered by DAF have higher anaerobic degradability	High energy consumption	Manjunath <i>et al.</i> , 2000
Sequencing batch aerobic reactor (SBR)	OLRs: 2.6 gCOD/(L.d) COD: 7,685 VSS: 1,520 TKN: 1,057 TP: 217	COD: >98% VSS: >97% P: >98% N: >97%	High biomass concentrations; shorter settle times; simultaneous nitrification and denitrification in SBR	If startup of SBR had not done properly, converting a flocculating SBR to a granular one could result in reactor failure due to excessive biomass washout.	Cassidy and Belia, 2005
Thermophilic aerobic treatment	COD: 3015 BOD ₅ : 1905 Orthophosphate: 5.2 SS: 283 Ammonia-nitrogen: 14.3	COD: >93% Phosphorus: 72-90% Ammonia: 2-30%	High removal efficiency of COD and orthophosphate	Removal decreased with temperature increase	Gariépy <i>et al.</i> , 1989
Anaerobic fluidized bed reactor	TS: 700-1930 TCOD: 430-850 SCOD: 340-680	Soluble organic: 75%	Suitable technology; no detrimental effect of temperature	Only considering net source of energy for middle- to high-strength wastewater	Toldrá <i>et al.</i> , 1987
Anaerobic batch reactor	TCOD: 1500	COD: around 80%	Sustainable high COD degradation rate	High COD level for direct discharge	Del Pozo <i>et al.</i> , 2003
UASB	OLRs: 13-30 gSCOD/(L.d) BOD ₅ : 914-1917 TCOD: 3265-14285 SCOD: 3000-4500	SCOD: 75-90%	Effectiveness; no sign of cell washout at high OLR and sludge loading rates	High OLR and low HRT were required for efficiency reduction; low VSS removal	Torkian <i>et al.</i> , 2003

Treatment Technology	Initial Concentration (mg/L)	Treatment Efficiency (% Removal)	Advantage	Disadvantage	References
UASB - anaerobic filter (AF)	OLRs: 5 gCOD/(L.d) COD: 8000 TSS: 573-1690 L	COD: 90% (UASB) COD: 84% (AF)	Good anaerobic biodegradability	Reactor destabilization, decrease of COD removal, a high wash-out of solids and sludge flotation at high OLR	Ruiz <i>et al.</i> , 1997
UASB – UASB	OLRs: 1.8 gCOD/(L.d) TCOD: 6700 SCOD: 2400 Fats: 1200 TSS: 1900	SCOD: 77% Insoluble COD: 82% Fat: 63% (red water)	Improvement of degradation of particulate matter due to recirculation in anaerobic reactors	Operating problem caused by high SS and fats, low SS removal	Martínez <i>et al.</i> , 1995
Anaerobic-aerobic fixed-film reactor	OLRs: 0.77 gCOD/(L.d) COD: 1820 BOD ₅ : 900 TKN: 190 TSS: 441	Total organic matter: 93% Nitrogen: 68%	High removal of organic matter	Difficult to regulate high internal recirculation flow between the aerobic and anaerobic zones; low extension of anaerobic process	Del Pozo and Diez, 2005
Combined anaerobic- aerobic fixed-film bioreactor	OLRs: 0.39 gCOD/(L.d) COD: 1040 BOD ₅ : 420 TKN: 180	Organic matter: 92% Nitrogen: 95%	High removal of organic matter	Unstable system with nitrification inhibition	Del Pozo and Diez, 2003
Fixed bed anaerobic reactor	OLRs: 2-18.5 g/L COD: 7500	COD: 30–85% (bamboo as carrier) COD: 27-80% (bones as carrier) SS: 46%	Suitable technology, enrichment of biomass	Reactor performs either positive or negative influence on the recirculation of outflow depending on substrate concentration in inflow	Tritt, 1992
Flocculant sludge UASB	OLRs: 3.5 gCOD/(L.d) TCOD: 1500-2200 TBOD: 490-650 TKN: 120-180 TP: 12-20	TCOD: 70% SCOD: 95% BOD ₅ : 95% Total N: 24%	Great practice in large pollutant loading; effective digestion; satisfied sludge retention	Inefficient in nitrogen reduction; occurrence of significant sludge increment	Sayed <i>et al.</i> , 1984

Treatment Technology	Initial Concentration (mg/L)	Treatment Efficiency (% Removal)	Advantage	Disadvantage	References
One stage granular UASB	OLRs: 11 gCOD/(L.d) TCOD: 1500-2200 TBOD: 490-650 SS: 40-50% of TCOD	COD: 56% SS: 41-51%	Effectiveness in removing the filtered COD; no sludge recirculation	Flocculent sludge presented due to high loading	Sayed <i>et al.</i> , 1987
Anaerobic baffled reactor (ABR)	COD: 4,000	COD: 97% (25°C) COD: 75% (15°C)	High COD removal and increase in system performance at high temperature	Efficiency decreased with temperature decrease	Nachaiyasit and Stuckey, 1997
Anaerobic baffled reactor (ABR)	OLR: 0.9-4.73 g/(L.d) COD: 480-730	COD: 75% Filtered COD: 84%	Effective; ability to retain active biological solids at high OLR; bacteria washout reduced	Total COD removal decreased with the increase of the OLR.	Polprasert <i>et al.</i> , 1992
Integrated UASB - AF	OLRs: 5-45 gCOD/(L.d) COD: 2450	COD: >96% SS: 10%	High removal rate; high efficiency in retaining biomass in AF	Low SS removal; COD removal decreased with the increase of COD loading rate.	Borja <i>et al.</i> , 1995a
UASB-coagulation-flocculation	OLRs: 1.46-2.43 gCOD/L.d COD: 1400-3600 O&G: 452-957 TN: 133-179	COD: 70-92% O&G: 27-58%	Improvement of characteristics of anaerobic sludge	Efficiency decreased due to more than 20% O&G ratio, which led to biomass washout and failure of the system	Miranda <i>et al.</i> , 2005
Anaerobic fluidized bed reactor	OLRs: 2.9-54 gCOD/(L.d) COD: 250-4500 BOD ₅ : 3120	COD: 75-98.9%	High COD removal; high methane-production rate; high biomass hold-up	Requires maintaining system buffering capacity	Borja <i>et al.</i> , 1995b
Expanded granular sludge bed	OLRs: 15 gCOD/(L.d) TCOD: 1.44-4.2 gO ₂ /L TBOD ₅ : 1.1-2.4 gO ₂ /L TSS: 370-840 l Fats: 45-280	COD: 65-80% TSS: 90% Fats: 85%	Effective; no accumulation of fats on the sludge; efficient retainability; high activity of sludge	TSS might washout.	Núñez <i>et al.</i> , 1999

Treatment Technology	Initial Concentration (mg/L)	Treatment Efficiency (% Removal)	Advantage	Disadvantage	References
Membrane bioreactor	OLRs: 6–8 gCOD/(L.d) COD: 5800-20150 BOD: 2200-9800 SS: 2.4-4.7 TKN: 301-460	COD: 97% SS: 45–55	High anaerobic conversion rates, unique feature of retention of biomass and SS, high COD removal, effectiveness	Process failure with excessive accumulation of substrate material, efficiency decrease with increase of particulate matter	Fuchs <i>et al.</i> , 2003
Anaerobic-anoxic sequencing batch reactor – fixed bed nitrification reactor	TCOD: 7780 SCOD: 6210 N-NH ₄ : 88 P-PO ₄ : 18 TSS: 0.87	COD: 99% N-NH ₄ : 85% P-PO ₄ : 99%	High efficiency; very good nutrient removal after prefermentation	Still high COD concentration in effluent; prefermentation of wastewater was required to achieve successful process operation; long HRT (50 days) for complete P removal.	Merzouki <i>et al.</i> , 2005
Anaerobic denitrifying reactor	Nitrogen loading rate: 33 mgN/(L.d) N-NH ₄ ⁺ : 163.7 COD: 614.5	Nitrogen: 95%	Sustainable treatment for nitrogen removal; COD is used as electron donor for denitrification	Removal efficiency of nitrogen decreased with the increase in nitrogen loading.	Reginatto <i>et al.</i> , 2005
Anaerobic fixed film reactor	OLRs: 8 gCOD/(L.d) COD: 2100 BOD ₅ : 1200 TSS: 950	COD: 85-95%	Very stable; very appropriate for pre-treatment; satisfied organic matter removal	Accumulation of suspended biomass	Del Pozo <i>et al.</i> , 2000
Anaerobic reactor with sludge blanket and filter bed	OLRs: 2.49-20.82 gCOD/L.d COD: 1041 BOD ₅ : 6600	COD: 90.2-93.4%	High COD removal	“Dead” space may be appearance at long HRT.	Borja <i>et al.</i> , 1998
Anaerobic sequencing batch reactor	OLRs: 2.07-4.93 g/(L.d) TCOD: 6908-11500	TCOD: 90–96% SCOD: > 95% SS: 53%	High degree of methanization	Solid accumulation, apparent biomass, and undegradable SS	Massé and Masse, 2000b

Notes:

BOD – biochemical oxygen demand

BOD₅ – biochemical oxygen demand in 5 days

COD – chemical oxygen demand

OLR – organic loading rate

O&G – oil and grease

SCOD – soluble chemical oxygen demand

SS – suspended solid

TBOD – total biochemical oxygen demand

TCOD – total chemical oxygen demand

TKN – total kjeldahl nitrogen

TN – total nitrogen;

TOC – total organic carbon;

TP – total phosphorus;

TSS – total suspended solid

VSS – volatile suspended solid

UASB – upflow anaerobic sludge blanket

AF – anaerobic filter

ABR – anaerobic baffled reactor

2.2.1 Kinetics of Anaerobic Digestion

Conceptually, the growth of microbe can be designated as four different phases (Reynolds and Richard, 1996): lag phase, exponential or log growth phase, stationary phase, and death phase as shown in Figure 2.1. Microbes are employed by anaerobic technologies to digest organic matter in the water and wastewater where there is no molecular oxygen. During anaerobic digestion, the microbes convert organic compounds into oxidized substances, new cells, energy for their life processes, and some gaseous end products such as methane and carbon dioxide (Reynolds and Richard, 1996). Reaction (2.1) is generalized for the anaerobic digestion process.

The sources of combined oxygen in this reaction include the radicals of CO_3^{-2} , SO_4^{-2} , NO_3^{-1} , and PO_4^{-3} . Some other products are H_2S , H_2 , and N_2 gases.

Figure 2.1: A typical microbial growth phases based on biomass concentrations.

The process of anaerobic digestion is accomplished by two groups of microorganisms, organic-acid-forming heterotrophs and methane-producing heterotrophs (Reynolds and Richard, 1996). The complex organic matter such as carbohydrates (sugars, starches, and cellulose or plant fiber), proteins, and their degradation products are used by the organic-acid-forming heterotrophs to form the products, organic acids named volatile fatty acids (VFA), which are used by the methane-producing heterotrophs to produce methane and carbon dioxide. The breakdown of carbohydrates and proteins in anaerobic conditions are shown in Reactions (2.2) and (2.3). The pathway for methane production from complex organic matter is shown in Figure 2.2. Methane producers grow more slowly than acid formers and require pH range of about 6.7 to 7.4.

Figure 2.2: Pathway of methane production from complex wastes (Reynolds and Richard, 1996).

Conceptually, nitrogen removal by biological processes requires the nitrogen to be in the form of nitrate (NO_3^-) (Reynolds and Richard, 1996). Aerobic biochemical reaction, called

nitrification converts carbonaceous and organic nitrogen matter to ammonia (NH_3) or ammonium ion (NH_4^+), then to nitrite (NO_2^-), and finally to NO_3^- . Another biochemical reaction, called denitrification converts NO_3^- to nitrogen gas (N_2). The biochemical reactions for nitrification and denitrification are shown in Reactions (2.4) and (2.5), respectively (Reynolds and Richards, 1996).

Organic matter in slaughterhouse wastewater could be represented by total organic carbon (TOC) and total nitrogen (TN) due to multiple organic compounds in the wastewater. Therefore, TOC and TN are firstly used by organic-acid-forming heterotrophs to produce VFAs and gaseous ammonia, and then VFAs are used by methane-producing heterotrophs to produce methane and carbon dioxide.

The relationship between the growth rate constant and the substrate concentration was given by Monod kinetics of anaerobic digestion developed in 1940s, and was developed from the young populations of microorganisms with rapid growth rate under the condition of an abundant substrate and applied to a single strain of bacteria growing on a single rate-limiting substrate (McCarty and Mosey, 1991). The Monod kinetic equation is shown in Equation (2.6) (Reynolds and Richards, 1996).

$$\mu = \mu_m \frac{S}{K_c + S} \quad (2.6)$$

where μ is specific growth rate of microorganisms, day^{-1} ; μ_m is the maximum specific growth rate of microorganisms, day^{-1} ; K_c is the substrate concentration when the growth rate constant is half of the maximum rate constant, g/L ; and S is substrate concentration, g/L .

Monod's original equation was derived from observation of young populations of microorganisms which grew very quickly in the presence of abundance of food supply (McCarty and Mosey, 1991). However, elderly populations of microorganisms were employed in many wastewater fermentations and grew slowly in semi-starvation conditions where a large proportion of substrate's energy is used by the microorganisms simply to stay alive. Therefore, the concept of "maintenance energy" whereby only the surplus substrate was available for microorganisms' growth was introduced by Pirt (1975) as shown in Equation (2.7).

$$\frac{dX}{dt} = Y \frac{dS}{dt} - mX \quad (2.7)$$

where:

- dX/dt is the rate of microorganism growth, $g/L.day$;
- dS/dt is the rate of substrate utilization, $g/L.day$;
- X is the concentration of microorganisms, g/L ;
- m is maintenance constant, day^{-1} ; and
- Y (dimensionless) is the yield coefficient and simply states that the growth rate of microorganisms is directly proportional to the rate of substrate utilization.

An almost similar model to Equation (2.7), which was derived from the fact that microorganisms could die of starvation or of old age, is presented in Equation (2.8) and is used for continuous culture growth under anaerobic conditions (McCarty, 1966; McCarty, 1991). Equations (2.7) and (2.8) differ only according to whether one believes the starving microorganisms are getting fewer, but they are indistinguishable mathematically (McCarty, 1991). Therefore, they tend to be used interchangeably. Combining Equation (2.8) and Michaelis-Menten Equation (2.9), Equation (2.10) is presented by McCarty (1966) to express

the relationship between the growth rate of microorganisms and the concentration of the substrate.

$$\frac{dX}{dt} = Y \frac{dS}{dt} - bX \quad (2.8)$$

$$\frac{dS}{dt} = \frac{V_{\max}XS}{K_m + S} \quad (2.9)$$

$$\frac{dX/dt}{X} = \frac{YV_{\max}S}{K_m + S} - b \quad (2.10)$$

where:

- $\frac{dX/dt}{X}$ is the specific growth rate of microorganism, day^{-1} ;
- S is the concentration of substrate surrounding microorganisms, g/L ;
- $V_{\max}$ is the maximum rate of substrate utilization at high substrate concentration, day^{-1} ;
- K_m is the concentration of substrate when dS/dt is half of the maximum rate, g/L ;
- b is microorganism decay rate, day^{-1} ; and
- others are the same as described in Equation (2.7).

A kinetic model for bacterial growth with continuous cultures in mineral salts media containing ammonium as a nitrogen source and glucose as a carbon source was developed by Contois (1959) based on the Monod kinetic model. The results indicated that the specific growth rate of bacteria was a function of population density and the concentration of limiting substrate. The Contois equation is shown in Equation (2.11).

$$R_s = \frac{u_m S_c}{(BP_m + S_c)} \quad (2.11)$$

where:

- R_s is specific growth rate of bacteria, h^{-1} ;

- S_c is the concentration of limiting substrate, mM ;
- P_m is density of bacterial population, mM ; and
- u_m and B are constant bacterial growth parameters (dimensionless).

A kinetic model for microorganism and methane produced in a magnetically stirred batch anaerobic digestion process was introduced by Fiestas *et al.* (1990). Methane production agreed with the first order kinetics as shown in Equation (2.12). The parameters G_m and K_{obs} can be determined numerically from experiment by using the international Time Series Processor (TSP) computer program version 4.0 D (Stanford, CA, USA), which is a complete language for the estimation and simulation of econometric models. The calculation must be made under loading density smaller than 9.6 gCOD/L to avoid an inapplicable model.

$$G = G_m [1 - \exp(-K_{obs} t_d)] \quad (2.12)$$

where:

- G is methane volume, L , which is accumulated at a given time;
- G_m is maximum methane volume, L , which is accumulated at an infinite digestion time;
- K_{obs} is specific rate constant, day^{-1} ; and
- t_d is digestion time, day .

A batch and upflow anaerobic sludge blanket (UASB) reactor was investigated for the treatment of slaughterhouse wastewater by Rodríguez-Martínez *et al.* (2002). It was demonstrated that the reactions in the UASB system agreed with the first order kinetics model for the production of methane and molecular nitrogen (N_2).

A kinetic model for the anaerobic digestion of organic substrates was developed by Barthakur *et al.* (1991) based on three stages of anaerobic digestion: (1) extracellular hydrolysis of complex compounds into soluble assimilable substrates, (2) transportation of assimilable substrates into microorganisms, and (3) utilization of assimilable substrates for microorganisms growth and generation of products. At the first stage, hydrolysis was assumed to be a first-order reaction as shown in Equation (2.13). At the second stage, the transportation of soluble substrates into microorganisms was assumed to the difference in the concentrations of the soluble substrate outside and inside the microorganisms and to the active biomass as shown in Equation (2.14). The growth of microorganisms was assumed to follow Monod Equation (2.6) as shown in Equation (2.15).

$$-\frac{dS}{dt} = K_h(S - S_h) \quad (2.13)$$

$$-\frac{dS}{dt} = k_h(S_h - S_u) = k_h S_h X \quad (2.14)$$

$$\mu = \mu_m \frac{S_h}{K_s + S_h} \quad (2.15)$$

Assuming maintenance energy and microbial decay were small so that biomass yield coefficient Y is constant. Therefore, substituting $X = Y_b(S_0 - S)$ into Equation (2.14) and combining Equations (2.13) and (2.15), a basic equation, Equation (2.16), for substrate utilization in the anaerobic digestion of complex organic compounds was given:

$$\frac{\mu_m}{\mu} = \frac{K_s K_h + k_h K_s Y_b (S_0 - S)}{K_h S} + 1 \quad (2.16)$$

where:

- S is the concentration of hydrolysable substrate, mg/L ;
- S_h is the concentration of hydrolyzed substrate, mg/L ;
- S_u is the concentration of hydrolyzed substrate entering the microorganisms, mg/L ;
- K_h is substrate hydrolysis rate coefficient, day^{-1} ;

- K_s is half-saturation constant for hydrolyzed substrate, mg/L ;
- k_h is the hydrolyzed substrate transport rate coefficient, day^{-1} ;
- Y_b is the biomass yield coefficient, $mg\ cell/mg\ substrate$; and
- Others are the same as defined as before.

For complex organic substrates, a part of substrates is refractory to biodegradation. The refractory coefficient R is expressed as $R = \frac{S_r}{S_{T0}}$, where S_r and S_{T0} are the refractory and total substrate concentration in the influent. Therefore, the two relationships, $S_0 = S_{T0}(1-R)$ and $S = S_T - RS_{T0}$ are given, where S_T is the total substrate concentration in the effluent. Substituting them into Equation (2.16), the basic Equation (2.17) for substrate utilization in anaerobic digestion is given as follows. Under steady-state conditions of continuous digestion in a completely mixed reactor without recycle, μ equals the reciprocal of hydraulic retention time t . Therefore, Equation (2.17) reduces to Equation (2.18), which had been used for semicontinuous (Barthakur *et al.*, 1991) and continuous (Setiadi *et al.*, 1996) anaerobic digestion. In this model, hydrolyzed products were considered as limiting substrates for microorganisms' growth and product formation. It was demonstrated by Barthakur *et al.* (1991) that poor and rate-limiting substrate hydrolysis and no hydrolysis of substrate took the form of Contois and Monod equations, respectively.

$$\frac{\mu_m}{\mu} = \frac{S_{T0}(1-R)A + K_s}{S_T} + R - A + 1 \quad (2.17)$$

$$\frac{S_T}{S_{T0}} = \frac{(1-R)A + \frac{K_s}{S_{T0}}}{\mu_m t + A - 1} + R \quad (2.18)$$

where:

- S_r is the refractory concentration in the influent mg/L ;
- S_T is the total substrate concentration in effluent, mg/L ;

- S_{T0} is the total substrate concentration in influent, mg/L ;
- t is the hydraulic retention time, day ;
- R is the refractory coefficient, dimensionless;
- $A (= \frac{K_s k_h Y_b}{K_h})$ is kinetic coefficient, to show the effluent substrate concentration is dependent on the influent substrate concentration; and
- Others are the same as described as above.

A first order model to describe the substrate concentration driving force within each compartment of anaerobic baffled reactor (ABR) in a continuous system was proposed by Kennedy and Barriault (2007). This model assumed that (1) the soluble component in an n -compartment ABR as a whole was the representative of n -CSTR-in-series, (2) the system would act as one large CSTR where the recycle was high compared to the influent flow, and (3) aceticlastic methane production was 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 the i^{th} compartment of an n -compartment-ABR are presented in Equations (2.19) and (2.20).

$$\frac{dS_1}{dt} V_1 = QS_0 + r_r QS_e - (1 + r_r)QS_1 - k_1 S_1 X_1 V_1 \quad (2.19)$$

$$\frac{dS_i}{dt} V_i = (1 + r_r)QS_{i-1} - (1 + r_r)QS_i - k_i S_i X_i V_i \quad (2.20)$$

For steady-state conditions, dS_1/dt and $dS_i/dt = 0$, then Equations (2.19) and (2.20) reduce to Equations (2.21) and (2.22), respectively, which are used to estimate the values of the first order rate coefficient of each compartment. In case of no recycle, $r_r = 0$, Equations (2.21) and (2.22) reduce to Equation (2.23).

$$S_1 = \frac{S_0 + r_r S_e}{(1 + r_r + k_1 X_1 V_1 / Q)} \quad (2.21)$$

$$S_i = \frac{S_{i-1}(1+r_r)}{(1+r_r+k_iX_iV_i/Q)} \quad (i \geq 2) \quad (2.22)$$

$$S_i = \frac{S_{i-1}}{(1+k_iX_iV_i/Q)} \quad (i \geq 1) \quad (2.23)$$

where:

- S_0 is the substrate influent concentration of ABR, g/L;
- S_e is the substrate effluent concentration of ABR, g/L;
- S_{i-1} is the substrate concentration in the $(i-1)^{th}$ compartment, g/L;
- S_i is the substrate concentration in the i^{th} compartment, g/L;
- r_r is the recycle rate of ABR, which is a percent of the flowrate of influent;
- k_i is the first order rate coefficient of substrate in the i^{th} compartment, L/(g.day);
- X_i is the biomass concentration of the i^{th} compartment, g/L;
- V_i is the volume of the i^{th} compartment, L; and
- Q is the flowrate of influent, L/day.

A model to evaluate the performance of an ABR was introduced by Bachmann *et al.* (1985). To apply this model for ABR evaluation, all compartments of ABR were considered completely mixed system as a result of quick gas generation at high loadings. The mass balance on substrate for ABR system was given in Equation (2.24).

$$\frac{dS_i}{dt} = -a_i R_c S_i^{q_i} + Q_i S_{i-1} - Q_i S_i \quad (2.24)$$

For steady-state conditions, $dS_i/dt=0$, then Equation (2.24) became Equation (2.25).

$$S_i = S_{i-1} - \left(\frac{a_i}{Q_i} \right) R_c S_i^{q_i} \quad (2.25)$$

where:

- Q_i is specific flow rate which is flow rate per unit volume of compartment i including recycle flow, s^{-1} ;

- a_i is specific biofilm surface area which is surface area per unit compartment i liquid volume, m^{-1} ;
- R_c is variable-order reaction coefficient which is a function of molecular diffusivity in biofilm (m^2/s), half-velocity coefficient (kg/m^3), maximum specific rate of substrate utilization (s^{-1}), bacterial density (kg/m^3), and the molecular diffusivity in bulk liquid (m^2/s);
- q_i is the variable reaction order which is a function of substrate concentration, the length of effective diffusion layer, and the parameters associated with R_c ; and
- S_{i-1} and S_i are the same as described as above.

2.2.2 Parameters of Anaerobic Wastewater Treatment

2.2.2.1 Organic Loading Rate

Organic loading rate (OLR) is a significant parameter on microbial ecology, especially in anaerobic wastewater treatment such as UASB system (Torkian *et al.*, 2003; Rajeshwari *et al.*, 2000). High OLRs containing suspended and colloidal components in the form of fats, proteins, and cellulose can have an adverse impact on the performance of UASB reactors, and therefore lead to the deterioration of microbial activity and active biomass washout (Lettinga *et al.*, 1997; Núñez and Martínez, 1999). Limited operational OLRs of 4–6 gCOD/(L.d) was demonstrated by Lettinga and Hulshoff Pol (1991). The OLRs of 5 gCOD/(L.d) with 90% COD removal at 37°C was reported by Ruiz *et al.* (1997). Up to 5 gCOD/(L.d) OLRs at 30°C was reported by both Sayed *et al.* (1987) and Sayed and De Zeeuw (1988). The OLRs of 12–17 gCOD/(L.d) with 65–99% COD removal was reported by Borja and Banks (1994). Up to the OLRs of 31 gBOD₅/(L.d) with 95% BOD₅ removal at 25–39°C without loss of stability was demonstrated by Chávez *et al.* (2005). An anaerobic fluidized bed reactor can withstand

a higher OLR with better stability, while achieving high COD reduction at a short hydraulic retention time of 0.2-5 *days* (Rajeshwari *et al.*, 2000). The typical COD loading rates and HRT for various anaerobic reactors are given in Table 2.6. As shown in this table, the COD loading rates in the UASB is higher than those in this study due to the granular sludge in the UASB reactor as compared to the flocculent sludge in the ABR.

Table 2.6: Typical COD loading rates and HRT for anaerobic bioreactors (Rajeshwari *et al.*, 2000).

Anaerobic Reactor	Typical COD Loading Rates (g/(L.d))	HRT (day)
Continuous stirred tank reactor (CSTR)	0.25-3	10-60
Contact anaerobic reactor	0.25-4	12-15
Upflow anaerobic sludge blanket (UASB)	10-30	0.5-7
Anaerobic filter	1-40	0.5-12
Anaerobic attached-film Expanded-bed reactor	1-50	0.2-5
Anaerobic fluidized bed	1-100	0.2-5
Anaerobic baffled reactor (this study)	0.2-1.1	0.9-3.8

2.2.2.2 Nutrients

Another important parameter in anaerobic digestion is nutrients. The presence of ions in feed can affect anaerobic digestion because ions can influence the granulation process and stability of reactors (Rajeshwari *et al.*, 2000). The bacteria in anaerobic digestion require nutrients such as nitrogen and phosphorous for their optimum growth. The lack of these nutrients will bring an adverse effect upon microbial growth and performance even though at only extremely low concentrations. The required optimum C:N:P ratio of 100:2.5:0.5 for enhanced yield of methane was reported by Somayaji (1992). To make sure small excess amount of the nutrients are available, the wastewater has to be supplemented with the

nutrients prior to treatment (Hulsho Pol, 1995).

However, higher concentration of nitrogen in the effluent of wastewater is undesirable because ammonia-nitrogen is toxic to fish and will be bio-oxidized by nitrifying microorganisms to form nitrates using molecular oxygen in the receiving water body, and nitrate-nitrogen are nutrients that stimulate algal and aquatic growths (Reynolds and Richard, 1996). As shown in Table 2.1, the general concentration of total nitrogen (TN) in the synthetic wastewater was largely higher than the disposal level in Canada shown in Table 2.2 and 2.3. Therefore, it is important to study the changes of TN in a wastewater treatment system.

2.2.2.3 Temperature and pH

Anaerobic digestion is classified as three main categories, psychrophilic (0-20°C), mesophilic (20-43°C), and thermophilic (43-75°C) (Hulsho Pol, 1995). Temperature is another strong parameter in anaerobic digestion. The lower the temperature is, the longer the digestion time is (Rajeshwari *et al.*, 2000). The temperature of slaughterhouse wastewater is typically between 20 and 36°C (Massé and Masse, 2001). The very low decay rate at the temperatures below 15°C is an important characteristic of anaerobic bacteria (Rajeshwari *et al.*, 2000). The removal efficiencies of COD decrease to 92, 85, and 78% along with the temperatures of 31, 21, and 12.5°C, respectively, in the stationary phase (Del Pozo *et al.*, 2006).

The pH is also an important parameter which anaerobic reactions are highly dependent on (Rajeshwari *et al.*, 2000). The optimum pH range for methane producing bacteria is

6.8-7.2 while acid-forming bacteria desire a lower pH (Mudrak and Kunst, 1986). In order to prevent the predominance of acid-forming bacteria which may cause the accumulation of volatile fatty acids, the pH of anaerobic digestion is typically maintained between methanogenic limits. Sodium bicarbonate is generally used as a buffer solution to supplement alkalinity for neutralizing any eventual VFA accumulation (Hulsho Pol, 1995).

2.2.3 Anaerobic Baffled Reactor (ABR)

Anaerobic baffled reactor (ABR) is a high-rate reactor that commonly contains 3 to 8 compartments in which liquid flow is alternately upwards and downwards between compartments (Barber and Stuckey, 1999). The more compartments an ABR has, the longer the hydraulic retention time is in the ABR, which further leads to a higher removal efficiency and higher capital, operation and maintenance costs. Several commonly used ABRs are presented in Figure 2.3. Their comparison is shown in Table 2.7. ABR could be considered consisting of n -upflow-reactors connected by baffles, and had been suggested to have a promise for industrial wastewater treatment (Bachmann *et al.*, 1985; Grobicki and Stuckey, 1991; Boopathy *et al.*, 1988). Each compartment may be designed to have similar or different working volume corresponding to similar or different residence time of wastewater, respectively. The residence time of an ABR depends on its wastewater flowrate and total working volume, which is the total working volume by the wastewater flowrate. Therefore, different configurations with similar total working volume may have different residence times. For each compartment of an n -compartment ABR with similar working volume, its residence time equals $\frac{1}{n}$ of the total residence time. Currently, ABR has been frequently used and presented its promise for wastewater treatment as shown in Table 2.8.

(a)

(b)

(c)

Figure 2.3: Several commonly used ABR: (a) individual gas headspace, which is used in this study; (b) original design; and (c) single gas headspace.

Table 2.7: Comparison of several ABR reactors (Barber and Stuckey, 1999).

Figure	Characteristics	Advantages
2.3(a)	(i) Narrowed downflow chambers (ii) Slanted edge baffle (40–45°) (iii) Individual biogas headspace	(i) To improve reactor performance; (ii) to measure biogas generation in each individual compartment to investigate its performance of methanogens; (iii) to enhance solids retention capacity
2.3(b)	(i) Original design (ii) Addition of vertical baffles to a plug flow reactor	To enhance reactor's ability and solids retention to maintain high populations of methanogens
2.3(c)	(i) Downflow chambers narrowed (ii) Slanted edge baffle (40–45°) (iii) Single biogas headspace	(i) To enhance reactor stability and solids retention; (ii) ease and control of gas measurement

ABR is effective for wastewater treatment under a wide range of flowrates and loadings. It has higher resilience to hydraulic and organic shock loads, longer biomass retention time, and lower sludge yields than many other high rate anaerobic reactors such as USAB (Barber and Stuckey, 1999). Also, ABR has the ability to separate acidogenesis and methanogenesis longitudinally down the reactor leading to a two-phase (volatile and non-volatile components) system and various bacteria groups in each phase (Foxon *et al.*, 2004; Bell and Buckley, 2003; Kennedy and Barriault, 2007; Hutòn *et al.*, 1999). The design and operation of ABR are very simple with low capital and operating cost (Barber and Stuckey, 1999). Mechanical mixing and maintenance during normal operation are not required (Foxon *et al.*, 2004). The main disadvantage of ABR is that it is not able to produce a floating sludge layer. In addition, the higher velocity of wastewater associated with the baffles could cause the solid washout.

Table 2.8: Summary of studies on ABR for wastewater treatment.

Type of Wastewater	Compartment /Dimensions (l×w×h)	Organic Loading Rate (OLR) (g/(L.d))	Influent COD Concentration (mg/L)	Hydraulic Retention Time (HRT) (days)	Efficiency (% Removal)	Note	References
Aircraft deicing fluid	4 compartments (without or with recycle) 60×25×30 cm with working volume 30.8 L	6.2 (or 9.9)	7000	27 (or 17) h	COD: 89% (without recycle) or 93% (with recycle)	Most of COD was removed in the first two compartments.	Kennedy and Barriault, 2007
Pharmaceutical wastewater	5 compartments 2.1×1.7×5.0 m with working volume 12,000 L	-	9736-19862	1.25 (or 2.5)	COD: 85.3-87.9% (or 89.9-91.2%) in ABR	ABR followed by Biofilm Airlift Suspension Reactor (BASR). The total COD removal efficiency is as great as 97.8%.	Zhou <i>et al.</i> , 2006
Synthetic wastewater containing <i>p</i> -nitrophenol (<i>p</i> -NP)	4 compartments 60×20×40 cm with active volume 38.4 L	0.039	3000	10.38	COD: 92%	74-93% COD was removed in compartment 1.	Kuşçu and Sponza, 2005
Synthetic wastewater containing <i>p</i> -nitrophenol (<i>p</i> -NP)	4 compartments 60×25×40 cm with active volume 45 L	0.3	3000	10.38	COD: 80~99% <i>p</i> -NP: 90~98%	The effluent from ABR was treated by CSTR.	Kuşçu and Sponza, 2006
Sanitation (on site) wastewater	8 compartments 3×1×1.2 m with total 600 L above the compartment		564	22 h	COD: 58% <i>E. coli</i> : 68% Total coliforms: 61%	The effluent must be further treated before discharge.	Foxon <i>et al.</i> , 2004
Brewery wastewater	4 compartments 60×20×100 cm with active volume 100 L	10.5	85000 (undiluted)	2	COD: 90%	In split fed ABR (split ratio in 4 compartment was 0.4, 0.3, 0.2, 0.1 OLR respectively), highest removal of COD occurred in compartment 3. In normally fed ABR, highest removal of COD occurred in the first compartment.	Uyanik, 2003

Type of Wastewater	Compartment /Dimensions (l×w×h)	Organic Loading Rate (OLR) (g/(L.d))	Influent COD Concentration (mg/L)	Hydraulic Retention Time (HRT) (days)	Efficiency (% Removal)	Note	References
Synthetic wastewater containing glucose	5 compartments 50×15×30 cm with working volume 10 L	3	3000	1	COD: 86%	65% COD was removed in the first compartment.	Vossoughi <i>et al.</i> , 2003
Nitrification and denitrification of municipal sewage	Each of 2 ABR filled with different materials had 4 compartments with 400 L.	-	300	15.2 h	COD: 78.6~83% BOD ₅ : 92.5~94% SS: 80.9~92.7%	Anaerobic baffled filter reactor followed by aerobic post-treatment system at low temperature condition (4.5-23°C)	Bodík <i>et al.</i> , 2003
Textile dye wastewater	8 compartments		4000	20 h	COD: >90% Color: 86%	The effluent would require further treatment before discharge.	Bell and Buckley, 2003
Pulp and paper black liquors	3 compartments 38×12×29.5 cm with working volume 10 L	5	32000-40000	2	COD: 69%	OLR above 6 g/L.d were toxic and destabilised the reactor. The highest COD removal at 35°C.	Grover <i>et al.</i> , 1999
Ice cream wastewater	4 compartments 60×20×100 cm with active volume 100 L	15	6200	10	COD: 99%	80% COD was removed in the first compartment.	Uyanik <i>et al.</i> , 2002
Dilute and soluble milk and colloidal rice and dog food	8 compartments with volume 40 L	2	500	6 h	COD: >80%	At HRT 80 hr, 95% COD removal can be achieved.	Langenhoff <i>et al.</i> , 2000
Palm oil mill wastewater	48×15×20 cm with total working volume 5 L	15.6 (COD)	15,103-65,100	10	COD: 33% (recycle ratio 5) or 70% (recycle ratio 20)	Recycle ratio greater than 15 was needed to maintain the system pH > 6.8 without alkalinity supplementation	Stetiadi <i>et al.</i> , 1996
Whisky distillery wastewater	10 compartments 62×20×42 cm with working volume 35 L	2.37	9500	4	COD: 92.25% BOD: 96.1%	Most of COD was removed in the first two compartments but occurred through out the entire length of the reactor.	Akunna and Clark, 2000

Type of Wastewater	Compartment /Dimensions (l×w×h)	Organic Loading Rate (OLR) (g/(L.d))	Influent COD Concentration (mg/L)	Hydraulic Retention Time (HRT) (days)	Efficiency (% Removal)	Note	References
Slaughterhouse wastewater	4 compartments with each 5.16 L	0.9-4.73	450-550	2.5-26 h	COD: 75-90%	Temperature at 25-30°C.	Polprasert <i>et al.</i> , 1992
Swine waste	2, 3, 4, 5 compartments of 4 ABRs, respectively, with total volume of 15 L for each ABR	4 (as VS)	59400	14	ABR with 2, 3, 4, 5 compartments with COD removal of 70, 74, 75, and 78% respectively. TKN removal of 52, 48, 50, 55% respectively.	ABR maintain a high void volume without the need for work-intensive gas collection system or sludge separation systems.	Boopathy, 1998
Synthetic slaughterhouse wastewater	5 compartments 50×15×50 cm with total volume 37.5 L	0.2-1.1 (as TOC)	2110-2305	0.85-3.77	TOC: 95%	Room temperature (20-30°C)	This study

2.3 UV/HYDROGEN PEROXIDE (UV/H₂O₂) PROCESS

Advanced oxidation process (AOP) is an oxidative method based on highly reactive radicals and holds the greatest promise to degrade organic compounds in water and wastewater and detoxify water and wastewater through generation of hydroxyl radicals, $\cdot\text{OH}$, which are powerful species for water and wastewater treatment and has an extreme effect on reducing organic compounds (Bolduc and Anderson, 1997; Zhou and Smith, 2002; Legrini *et al.*, 1993; Glaze, 1987; Varatharajan and Kanmani, 2007). The advantages of AOPs include high removal rate, large range of applicability, thorough mineralization of pollutants in water and wastewater, and changing nonbiodegradable, recalcitrant, and refractory compounds into more biodegradable components as well as a high reaction rate (Stefan *et al.* 1996; De Morais and Zamora, 2005; Aye *et al.*, 2004). In comparison to the conventional biological treatment, an important disadvantage of AOPs is their high capital and operating costs (Tabrizi and Mehrvar, 2004). The main AOPs include ozonation, ozone (O_3)/hydrogen peroxide (H_2O_2) process, ultraviolet light (UV)/ H_2O_2 process, UV/ O_3 , UV/ H_2O_2 / O_3 , Fenton/UV/ H_2O_2 process, UV/ TiO_2 process, vacuum UV process, and some others (Legrini *et al.*, 1993; Zhou and Smith, 2002). Advanced oxidation processes (AOPs) may be also applied as final treatment technique after biological units before wastewater discharge, which should reduce COD to satisfy local regulations on discharge (Raj and Quen, 2005).

The UV/ H_2O_2 is one of the most appropriate AOP processes that has been frequently used as an effective technique for various wastewater treatments recently. For example, a photocatalytic system under the presence of UV radiation for the treatment of a textile dye (reactive yellow 2) wastewater was investigated, and the results showed that both decolorization and mineralization were significantly improved by using optimum H_2O_2

concentration of 15 mM, and followed the first order kinetics (Aye *et al.*, 2003). The treatment of atrazine in water using a UV/H₂O₂ process was investigated by Beltrán *et al* (1993) and they reported more than 99% of atrazine degradation in less than 15 minutes. The decolorization and mineralization of cotton dyeing effluent containing C.I. Direct Blue 199 through a UV/H₂O₂ were also studied by Shu (2006) and the results showed that the color was removed very quickly and TOC removal was reached about 75 and 80% in 30 and 120 minutes, respectively. The treatment of raw surface water containing disinfection byproducts (DBPs) using a UV/H₂O₂ process with UV dosage of 0-3,500 mJ/cm² and H₂O₂ concentration of 0-23 mg/L was studied and the results showed that the UV/H₂O₂ process was effective in reducing DBPs at UV dosage of more than 1,000 mJ/cm² and initial H₂O₂ concentrations of about or greater than 23 mg/L (Toor and Mohseni, 2007). The degradation of a 100 mg/L solution of linear alkylbenzene sulfonate (LAS) by using a UV/H₂O₂ process with the wavelength of 254 nm was investigated by Venhuis and Mehrvar (2005) and an optimum H₂O₂ concentration of 5000 mg/L was reported based on the first order kinetics. Another optimum H₂O₂ concentration of 720 mg/L for the degradation of a 100 mg/L solution of LAS in a pilot-plant photoreactor with the wavelength of 254 nm was reported by Tabrizi and Mehrvar (2006).

The mechanism most commonly accepted for the photolysis of H₂O₂ is the cleavage of one H₂O₂ molecule into two hydroxyl radicals (·OH) per quantum of radiation absorbed, which is shown in Reaction (2.26) (Legrini *et al*, 1993; Esplugas *et al.*, 2002; Crittenden *et al*, 1999; Tabrizi and Mehrvar, 2004). When an organic compound (RH) presented in water and wastewater, the reactions between generated hydroxyl radicals and organic pollutants may be differentiated by the mechanisms of Reactions (2.26) to (2.36). The major reactions including literature values of relevant quantum yields or rate constants for organic compounds (RH)

involved in a UV/H₂O₂ process are summarized in Table 2.9 (Legrini *et al*, 1993; Crittenden *et al*, 1999; Johnson and Mehrvar, 2008).

Table 2.9: Major reactions in UV/H₂O₂ process.

Reaction No.	Reaction	Rate constants (/ (Ms))	Reference
(2.26)	$\text{H}_2\text{O}_2 + h\nu \xrightarrow{\varphi_1} 2\cdot\text{OH}$	$\varphi_1 = 0.5 \text{ mol/photon}$	Beltrán <i>et al.</i> , 1999
(2.27)	$\text{H}_2\text{O}_2 + \cdot\text{OH} \xrightarrow{k_2} \text{H}_2\text{O} + \cdot\text{HO}_2$	$k_2 = 2.7 \times 10^7$	Buxton <i>et al.</i> , 1988
(2.28)	$\cdot\text{OH} + \cdot\text{OH} \xrightarrow{k_3} \text{H}_2\text{O}_2$	$k_3 = 5.0 \times 10^9$	Stachelin <i>et al.</i> , 1984
(2.29)	$\cdot\text{HO}_2 + \cdot\text{HO}_2 \xrightarrow{k_4} \text{H}_2\text{O}_2 + \text{O}_2$	$k_4 = (8.3 \pm 0.7) \times 10^5$	Bielski <i>et al.</i> , 1985
(2.30)	$\text{H}_2\text{O}_2 + \cdot\text{HO}_2 \xrightarrow{k_5} \text{H}_2\text{O} + \text{O}_2 + \cdot\text{OH}$	$k_5 = 3.0 \pm 0.6$	Koppenol <i>et al.</i> 1978
(2.31)	$\cdot\text{HO}_2 + \cdot\text{OH} \xrightarrow{k_6} \text{H}_2\text{O} + \text{O}_2$	$k_6 = 7.1 \times 10^9$	Sehested <i>et al.</i> , 1968
(2.32)	$\cdot\text{OH} + \text{RH} \xrightarrow{k_7} \text{intermediates} \rightarrow \text{CO}_2 + \text{H}_2\text{O}$	k_7	
(2.33)	$\text{RH} + h\nu \xrightarrow{\varphi_2} \text{intermediates} \rightarrow \text{CO}_2 + \text{H}_2\text{O}$	φ_2	
(2.34)	$\text{HCO}_3^- + \cdot\text{OH} \xrightarrow{k_8} \cdot\text{CO}_3^- + \text{H}_2\text{O}$	$k_8 = 8.5 \times 10^6$	Buxton <i>et al.</i> , 1988
(2.35)	$\text{CO}_3^{2-} + \cdot\text{OH} \xrightarrow{k_9} \cdot\text{CO}_3^- + \text{OH}^-$	$k_9 = 3.9 \times 10^8$	Buxton <i>et al.</i> , 1988
(2.36)	$\cdot\text{CO}_3^- + \text{H}_2\text{O}_2 \xrightarrow{k_{10}} \text{HCO}_3^- + \cdot\text{HO}_2$	$k_{10} = 4.3 \times 10^5$	Crittenden <i>et al.</i> , 1999

where φ is the quantum yield constant, (mol of H₂O₂ or RH)/photon; and k is reaction rate constant, (M.s)⁻¹.

A kinetic model for a single UV lamp tubular photoreactor was introduced by Johnson and Mehrvar (2008). The mass balance and radiation energy balance in the z-axial direction centered at the origin are given in Equations (2.37) and (2.38), respectively. The integration yield of Equation (2.38) is given in Equation (2.39).

$$\frac{\partial C_i}{\partial t} + \left(v_r \frac{\partial C_i}{\partial r} + v_\theta \frac{1}{r} \frac{\partial C_i}{\partial \theta} + v_z \frac{\partial C_i}{\partial z} \right) = D_{AB} \left(\frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial C_i}{\partial r} \right) + \frac{1}{r^2} \frac{\partial^2 C_i}{\partial \theta^2} + \frac{\partial^2 C_i}{\partial z^2} \right) - R_{rxn,i} \quad (2.37)$$

$$\frac{1}{r} \frac{d(rq)}{dr} = -q(2.303\mu_s) \quad (2.38)$$

$$q = q_o \frac{R_i}{r} e^{-2.303\mu_s(r-R_i)} \quad (2.39)$$

where:

- C_i is the concentration of organic compound i , M ;
- t is retention time, s ;
- r is radial position, m ;
- R_i is inner reactor radius, m ;
- v_r , v_θ and v_z are velocities in r -, θ - and z -directions, respectively, m/s ;
- D_{AB} is the diffusivity of organic compound in aqueous solution, m^2/s ;
- $R_{rxn,i}$ is the reaction rate of organic compound i , M/s ;
- q is radiant energy flux, $(mol\ photons)/(m^2s)$;
- q_o is the radiant energy flux at outer surface of UV lamp, $(mol\ photons)/(m^2.s)$; and
- μ_s is the extinction coefficient of aqueous solution, m^{-1} .

If the concentration of intermediates was assumed to be very low, the UV absorptive properties of reaction intermediates could be neglected (Johnson and Mehrvar, 2008). Therefore, the local extinction coefficient of aqueous solution, μ_s , can be expressed by Equation (2.40). The local volumetric rate of energy absorption (LVREA), A_L , is a function of radiant energy flux, which is expressed in Equation (2.41) (Mehrvar *et al.*, 2002). Using Equations (2.40) and (2.41), the LVREA can be expressed by Equation (2.42). The fraction of photons absorbed by compound i at any given position within UV photoreactor, f_i , is given in Equation (2.43). The LVREA at any length, L_i , can be expressed by Equation (2.44) and the average LVREA throughout the photoreactor can be determined by Equation (2.45) (Shemer *et al.*, 2006).

$$\mu_s = \mu_w + \varepsilon_{H_2O_2} C_{H_2O_2} + \varepsilon_{RH} C_{RH} \quad (2.40)$$

$$A_L = \mu_s q \quad (2.41)$$

$$A_L = \mu_s q_o \frac{R_i}{r} e^{-2.303 \mu_s (r - R_i)} \quad (2.42)$$

$$f_i = \frac{\varepsilon_i C_i}{\mu_s} \quad (2.43)$$

$$A_L = \mu_s q_o e^{-\mu_s L} \quad (2.44)$$

$$\bar{A} = \frac{\int_0^L \mu_s q_o e^{-\mu_s L} dL}{\int_0^L dL} = \frac{q_o}{L} (1 - e^{-\mu_s L}) \quad (2.45)$$

In these equations, μ_w is the extinction coefficient of water, m^{-1} ; ε is the molar absorption of target compound, $(M.m)^{-1}$; A_L is the local volumetric rate of energy absorption; and others are the same as described before.

Bolton *et al.* (2001) proposed simple rate equations that were either zero-order or first-order in an organic contaminant to describe the overall kinetic of a specific component such as TOC in advanced oxidation processes (AOPs) such as UV/H₂O₂ process. Based on the major reactions shown in Table 2.9, the models of Bolton *et al.* (2001) for UV/H₂O₂ process are shown in Equations (2.46) to (2.50).

Where:

- $R_{rxn,1}$ is the reaction rate of $\cdot\text{OH}$, mg/L.h ;
- $R_{rxn,2}$ is the reaction rate of $\cdot\text{OH}$ with RH, mg/L.h ;
- $R_{rxn,3n}$ is the reaction rate of $\cdot\text{OH}$ with a scavenger S_n , where $n = a, b, \dots, n$, mg/L.h ;
- ξ is a constant that depends on the type of AOPs, mg/h.W ;
- p is the power rating for the system, W ;
- V_{UV} is treated wastewater volume, where equals the volume of UV photoreactor, L ;
- RH is a target organic compound, the concentration unit: mg/L ;
- S_n is a scavenger for the $\cdot\text{OH}$, where $n = a, b, \dots, n$, the concentration unit: mg/L ; and
- k_{RH} and k_{S_n} are second-order rate constant, $L/\text{mg.h}$.

A steady-state condition analysis generates the overall rate kinetic for the UV/H₂O₂ process as shown in Equation (2.51), which is either zero- or first-order for the contaminant RH. If the concentration of RH is high, $k_{RH}[\text{RH}] \gg \sum_n k_{S_n}[S_n]$, the reaction rate will be zero-order in RH as shown in Equation (2.52). If the concentration of RH is low, $k_{RH}[\text{RH}] \ll \sum_n k_{S_n}[S_n]$, the reaction rate will be first-order in RH as shown in Equation (2.53).

The difference between high and low concentration varies with the process but is often around 100 mg/L (Bolton *et al.*, 2001).

$$-\frac{d[\text{RH}]}{dt} = \frac{\xi p k_{RH} [\text{RH}] / V_{UV}}{k_{RH} [\text{RH}] + \sum_n k_{S_n} [S_n]} \quad (2.51)$$

$$-\frac{d[\text{RH}]}{dt} = \frac{\xi p}{V_{UV}} \quad (2.52)$$

$$-\frac{d[\text{RH}]}{dt} = \frac{\xi p k_{RH}}{V_{UV} \sum_n k_{S_n} [S_n]} [\text{RH}] \quad (2.53)$$

Where all parameters are the same as described as above.

A number of advantages in water and wastewater treatment are presented by UV/H₂O₂ process, such as offering great potentials in wastewater treatment especially disinfection, enhancing the degradation of pollutants, accelerating the rate of oxidation of wastewater, reducing the concentration of pollutions, thermal stability and storage on-site, high solubility of H₂O₂ in water, no mass transfer problems related to gases, applicability for most organic substrates, and simple operation procedure (Toor and Mohseni, 2007; Sonntag *et al.*, 1993; Raj and Quen, 2005; Legirini *et al.*, 1993). Certainly, there are also limitations of the application of UV/H₂O₂ process. For example, the rate of the formation of hydroxyl radicals limits the rate of the chemical oxidation of pollutants (Legirini *et al.*, 1993). At higher concentrations, H₂O₂ acts as a strong scavenger for hydroxyl radical which can reduce the degradation of organics (Glaze *et al.*, 1987; Stefan *et al.*, 1996). Also, the presence of carbonate and bicarbonate ions has been observed as hydroxyl radical scavengers, which could slow down the degradation rate of some organic matters (Mehrvar *et al.*, 2001).

2.4 IS THERE ANY NEED FOR COMBINED TECHNOLOGIES FOR THE TREATMENT OF SLAUGHTERHOUSE WASTEWATER?

An overview of slaughterhouse wastewater treatment and its characteristics, by-products, environmental impacts, and health effects was provided in this chapter. The studies on the treatment technologies of slaughterhouse wastewater, anaerobic digestion and UV/H₂O₂ process were also reviewed in this chapter. After examining most previous studies, it was found that the general characteristics of the effluent from slaughterhouse wastewater in most of processes still had significant concentrations of COD, BOD₅, nitrogen, and pathogen and

could not meet the recommended disposal level in Canada even if they presented high removal efficiencies. Meanwhile, the remaining processes had lower removal efficiencies of the COD, BOD₅, and nitrogen. Therefore, a new combined technology is needed to treat slaughterhouse wastewater sufficiently before the effluent is discharged into receiving waters.

Many investigators studied combined processes of biological process and UV/H₂O₂ for wastewater treatment. An integrated system of UV/H₂O₂ process and activated sludge bioreactor was investigated and presented a cost-effective process for aqueous degradation of phenol (Edalatmanesh *et al.*, 2008). A combined system of photochemical and biological processes was studied to treat linear alkylbenzene sulfonate (LAS) in water (Mehrvar and Tabrizi, 2006) and the results showed that the biodegradability of the untreated LAS solution with the lower effluent concentration (10 mg/L) in a photoreactor was higher than that of biological pretreated LAS solution with the same effluent concentration in the photoreactor due to the presence of some intermediates.

The advantages of combined system of biological and AOP processes include (Lee *et al.*, 2001; Tabrizi and Mehrvar, 2004):

- flexibility of total residence time to bring a constant efficiency for chemical and biological reactor;
- decreasing in chemical cost through cost-effective biological pretreatment; and
- achieving total mineralization for organic compounds by minimizing total cost.

2.5 CONCLUDING REMARKS

After examining different processes for the treatment of slaughterhouse wastewater, a

combined anaerobic baffled reactor (ABR) and UV/H₂O₂ was selected for the treatment of synthetic slaughterhouse wastewater in this study. Due to the biodegradability of the synthetic wastewater, the ABR was placed before the UV photoreactor which was used as the final treatment technology.

The model Equations (2.17) and (2.18) proposed by Barthakur *et al.* (1991) was investigated to evaluate the performance of the ABR process. The objectives of this study are mentioned in Chapter 1.

CHAPTER 3

EXPERIMENTAL SETUP AND METHODOLOGY

3.1 MATERIALS

A synthetic slaughterhouse wastewater employed in this study was prepared based on the study of Stephenson and Lester (1985). It contained (*mg/L* distilled water): 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; and magnesium sulfate ($MgSO_4 \cdot 7H_2O$), 7.5. According to the information from the manufacturer, Oxoid Ltd., the commercial meat extract contained 17 amino acids including alanine, arginine, aspartic acid, cysteine, glutamic acid, glycine, isoleucine, leucine, lysine, methionine, phenylalanine, proline, serine, threonine, tryptophan, tyrosine, and valine. Twenty, 40, 60, 80, and 100% of the amount of each component in the synthetic wastewater were used respectively to prepare various levels of the synthetic wastewater.

The analysis of the meat extract provided by the manufacturer, Oxoid Ltd. (Nepean, Ontario, Canada), gave 13.3% w of total nitrogen (TN)/w of meat extract and a pH of 7.2 ± 0.2 . The TN of the meat extract based on the above 17 amino acids was calculated to be 10.9% w of TN/w of meat extract as shown in Table A.1 in Appendix A. The difference between these two values of TN indicates that there would be unknown organic compounds in the meat extract.

To investigate the characteristics of the synthetic wastewater, the pH value and the concentrations of TOC, TN, COD, and CBOD₅ were measured. The results compared with literature values are shown in Table 3.1. The results showed that the literature values of COD is greater than that in this study due to the operating error of weighing each components and system error of top-loading balance. The TOC of the meat extract based on the above 17 amino acids was calculated to be 31.5% w of TOC/w of meat extract as shown in Table A.1 in Appendix A. Considering the amounts of glycerol and ammonium chloride used in the initial synthetic wastewater, the TOC and TN concentrations were calculated to be 692 mgC/L and 354 mgN/L (determined by 13.3% w of TN/w of meat extract). It shows that there was a big difference between the TOC measurement (950-980 mgC/L) and the estimated value (692 mgC/L) due to unknown organic compounds in the meat extract. The calculations of TOC and TN concentrations of the initial synthetic wastewater are shown in Appendix A.

Table 3.1: Characteristics of initial synthetic slaughterhouse wastewater.

Characteristics	Literature values	Values in this study
COD (mgO ₂ /L)	2500 ^a	2110 - 2305
CBOD ₅ (mgO ₂ /L)	N/A	1026 - 1143
TOC (mgC/L)	692 ^b	950 - 980
TSS (mgSolids/L)	0 ^a	0
TN (mgN/L)	354 ^b	334 - 380
pH	6.23 - 7.26 ^a	6.4 - 7.5
Alkalinity (mgCaCO ₃ /L)	50 ^a	N/A

^a From Stephenson and Lester (1985);

^b Calculation based on the information from meat extract manufacturer and the amount of glycerol and ammonium chloride used in the synthetic wastewater as shown in Appendix A.

Ratios of TOC, COD, and BOD₅ can be used to assist in characterizing a waste (Metcalf and Eddy, 1993; Eckenfelder, 2000). The ratio of COD/TOC gives an indication of the

average state of carbon in a solution. BOD depends on the biodegradability of a waste. The ratio of BOD/COD (commonly BOD₅/COD) gives an indication of the biodegradability of the waste. The ratio of COD/TOC ranges from 0 to 5.33 for methane when an organic matter is resistant to dichromate oxidation, and the ratio of BOD₅/COD of a readily biodegradable waste is 0.5 or greater. If wastewater contains nitrogen contents and nitrification is inhibited during BOD₅ testing, 5-day carbonaceous biochemical oxygen demand (CBOD₅) will be used to replace BOD₅ (APHA *et al.*, 1998). In this study, the ratio of CBOD₅/COD of the undiluted synthetic wastewater was about 0.4-0.5, which indicates that the synthetic wastewater was biodegradable, and the ratio of COD/TOC of the undiluted wastewater was about 2.2-2.4. After mixing with H₂O₂ solution, this ratio of CBOD₅/COD of the undiluted synthetic wastewater decreased to 0.3-0.4, which indicated that the biodegradability of the synthetic wastewater was decreased by H₂O₂ solution.

Anaerobic sludge was obtained from a municipal wastewater treatment plant in Toronto, Ontario and was loaded manually into the anaerobic baffled reactor (ABR). The redundant sludge was stored in a closed container and was fed by the synthetic wastewater periodically at room temperature for possible use in the future. The suspended solid concentration of the anaerobic sludge was 20,000 mg/L.

A hydrogen peroxide solution (1110 g/L of density) containing 30% w/w of H₂O₂ (EMD Chemicals, Inc.) was used in UV/H₂O₂ process. The concentration of H₂O₂ in the wastewater was determined as follows.

$$C_{H_2O_2} = \frac{Q_{H_2O_2} \times \frac{D \times V_{H_2O_2}}{V_{H_2O_2} + V_{DWater}}}{Q_{H_2O_2} + Q} \quad (3.1)$$

where:

- $C_{H_2O_2}$ is H_2O_2 concentration in wastewater, g/L;
- $Q_{H_2O_2}$ is the flowrate of H_2O_2 solution, L/min;
- Q is the flowrate of wastewater, L/min;
- $V_{H_2O_2}$ is the volume of commercial H_2O_2 solution, L;
- V_{DWater} is the volume of distilled water, L; and
- D is the density of commercial H_2O_2 solution, g/L, in this study, $D= 1110$ g/L.

3.2 EXPERIMENTAL SETUP

The schematic diagram of the combined processes of the ABR and the UV/ H_2O_2 is shown in Figure 3.1. Although wastewater recycle could reduce the influent concentration and further decrease HRT and operation cost of a process, recycle stream was not used for the combined processes in this study due to the consideration of total capital costs and experimental time. The ABR with individual gas headspace was designed based on the previous studies summarized in Table 2.7 which shows that the ratios of length to width (L/W), width to height (W/H), and length to height (L/H) of those ABRs are 1.2-3.3, 0.2-0.8, and 0.4-2.5, respectively. Due to the consideration of wastewater retention time, removal efficiency of wastewater, and total costs, the ABR was designed to contain 5 equal-volume compartments with dimensions of 50 cm in length, 15 cm in width, and 50 cm in height, which gave the ratios 0.3, 0.3, and 1.0 of L/W, W/H, and L/H, respectively, indicating that the design of the ABR could be reliable for the synthetic wastewater. In order to mix the wastewater, each compartment was further divided into 2 small compartments with 2 and 8 cm width, respectively, by a 45° slanted edge baffle (6), leading to the downflow and upflow of the wastewater passing through anaerobic sludge layer in each compartment. The total volume of the ABR was 37.5 L with a total working volume of 33.7 L.

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 .

The synthetic wastewater homogenized by a recirculating pump (18) at room temperature was fed continuously from a wastewater feed tank (1) into the ABR (5) by a peristaltic pump (2) and flowed downwards and upwards within 5 compartments. Each compartment had an anaerobic sludge layer (9). The flowrate of the wastewater was measured by a acrylic flow meter (3) (FL-2018, Omega) connected to a peristaltic injector pump with 115V60Hz and 80 Watts (Flexflo A-100E, Blue-White Industries Ltd). The wastewater samples of each compartment were taken by gravity from wastewater sampling valves (8) located 40 *cm* from the bottom of each compartment and 4 *cm* from the side of its slanted edge baffle. The sludge samples of each compartment were taken by gravity from sludge sampling valves (7) located 10 *cm* from the bottom of each compartment and 4 *cm* from the side of its slanted edge baffle. The ABR-treated wastewater discharged into a treated wastewater collection tank (14) in the ABR process or flowed into a UV photoreactor (12), which was controlled by different valves (4, 10, 11), then discharged into the treated wastewater collection tank in the combined processes. In the combined processes, the relationship of the hydraulic retention time between ABR reactor and photoreactor is expressed by Equation (3.2) when the flowrate of H₂O₂ (lower than 10% of the wastewater flowrates) was negligible.

$$\frac{V_{ABR}}{t_{ABR}} = \frac{V_{UV}}{t_{UV}} \quad (3.2)$$

where:

- V_{ABR} is the volume of the ABR reactor, *L*;
- V_{UV} is the volume of the UV photoreactor, *L*;
- t_{ABR} is the retention time of the ABR process, *h*; and
- t_{UV} is the retention time of the UV/H₂O₂ process, *h*.

A UV photoreactor (Siemens, SL-LAB-.5) with a total working volume of 1.35 *L* with 8 *cm* external diameter and 34 *cm* total length was connected to the ABR. A UV lamp (13) with

output power of 6 *W*, and 2.5 *cm* in diameter covered by a quartz sleeve was inserted into the center of the cylindrical UV photoreactor. The wavelength of UV light was 254 *nm*. In the combined processes, diluted H_2O_2 solutions were continuously added into the UV photoreactor by gravity from a H_2O_2 solution container (15), and its flowrate was controlled by a valve (16) to be as slow as possible not to affect the wastewater concentration and was measured manually. In the UV/ H_2O_2 process alone, the wastewater mixed with H_2O_2 continuously fed to the UV photoreactor by gravity from the same H_2O_2 solution container (15). The flowrate was also controlled by valve (16) and was measured by hand.

Biogas produced in each compartments of the ABR was collected by a gas collection container (17) filled with water, and its total volume was determined by the volume of the water displaced from the gas collection container.

3.3 EXPERIMENTAL PROCEDURE

3.3.1 Acclimatization of Anaerobic Sludge in the ABR

First the ABR was filled with 10 *L* of fresh anaerobic sludge, with 2 *L* in each compartment (about 30% of the working volume of each compartment). After sealing the ABR, in order for the microorganisms to gradually adapt to the synthetic wastewater, the anaerobic sludge was acclimatized first by running the ABR continuously at a constant flowrate of 8.8 *mL/min* by gradually increasing in the synthetic wastewater concentration entering the ABR from 20, 40, 60, and 80 to 100% of the undiluted synthetic wastewater. Twenty, 40, and 60% levels remained for 14 days, while 80% level remained for 10 days. A 100% level was set at day 53 and remained for 15 days. From day 69, the VSS of the anaerobic sludge was observed to reach a high level and looked like to fall in the stationary

phase of the bacterial growth curve (see Figures 2.1 and 4.5). Therefore, the anaerobic sludge was considered ready for the future experiments on the undiluted synthetic wastewater, and all experiments were in actual experiment.

Samples of anaerobic sludge in each compartment were taken during the acclimatization to measure their total suspended solid (TSS) and volatile suspended solid (VSS) concentrations. The trend of VSS in the acclimatization was used to observe the growth of microorganisms. As part of TSS, an increase in the VSS of the sludge shows the growth of the microorganisms and a successful acclimatization for the anaerobic sludge (see Figure 4.5). The anaerobic sludge should be partially removed from the ABR if sludge washout were observed in the effluent of the ABR. Otherwise the TSS and VSS of the effluent of the ABR would increase and post-treatment may be needed to remove TSS and VSS from the effluent because high TSS concentration will block UV light and further reduce the treatment efficiency of the UV/H₂O₂ process.

3.3.2 ABR Process

As soon as the 68 days of acclimatization was achieved, the ABR process was run with various influent concentrations of the synthetic wastewater at various flowrates of 6.2, 8.8, 10.5, 13.5, and 27.6 *mL/min*, respectively, corresponding to the hydraulic retention times (HRT) of 3.8, 2.7, 2.2, 1.7, and 0.9 days, respectively. The TOC loading rates of the synthetic wastewater were ranged from 0.2 to 1.1 *g/(L.day)* with the change of wastewater influent concentration and HRT. For example, a ABR process was run at the flowrate of 27.6 *mL/min* and the influent concentration of the initial synthetic wastewater of 948.3 *mg/L*, which led to 0.9 days of HRT and 1.1 *g/(L.day)* of TOC loading rate. At each HRT, after the ABR system

was run for at least HRT long, first about 5-10 mL of the wastewater in each compartment were discharged to eliminate the effect of the sampling valves, and then about 20-30 mL of the wastewater in each compartment was quickly taken during the process to measure the concentrations of TOC, TN, COD, CBOD₅, TSS, and VSS, whilst the dissolved oxygen (DO), temperature, and pH of the wastewater were also measured. For each sample, two measurements of TOC, TN, CBOD₅, TSS, and VSS were made. An example calculation for sample standard deviation is shown in Appendix B.

3.3.3 UV/H₂O₂ Process

The UV/H₂O₂ process was operated at various influent concentrations of the synthetic wastewater and H₂O₂ at the HRT of 0.5, 1.0, 1.5, 2.0, 2.5 h, respectively. H₂O₂ dosages of 529 and 1371 mgH₂O₂/L of wastewater were used respectively, which were the lowest and highest findings of H₂O₂ dosages in the experimental trials of the combined processes. The TOC loading rates of 0.06 to 1.9 g/(L.h) with the change of influent concentration and HRT. For example, a UV/H₂O₂ process was run at HRT of 2.5 h and the influent concentration of diluted synthetic wastewater was 155.0 mg/L, which led to 0.06 g/(L.h) of TOC loading rate. After mixing with each H₂O₂ dosage and being stirred manually for no less than 15 minute, the synthetic wastewater was continuously fed to the UV photoreactor by gravity from the H₂O₂ solution container at various HRT adjusted manually by the valve (16). The experiment without UV irradiation, called dark experiment, was first conducted to investigate the possible adsorption of organic compounds on the UV photoreactor walls. At each HRT, after the UV/H₂O₂ process was run for at least HRT long, about 20-30 mL of the wastewater was quickly taken during the process to measure the concentrations of TOC, TN, COD, and CBOD₅, whilst the temperature and pH of the wastewater were also measured. For each

sample, two measurements of TOC, TN, and CBOD₅ were made.

3.3.4 Combined Processes of ABR and UV/H₂O₂

The combined processes of the ABR and the UV/H₂O₂ were operated at various flowrates of 6.2, 8.8, 10.5, 13.5, and 27.6 *mL/min* corresponding to the HRT of 3.8, 2.7, 2.2, 1.7, and 0.9 *days* in the ABR, and 218, 153, 129, 100, and 49 *min* in the UV photoreactor, respectively. The TOC loading rates in the ABR in the combined processes were similar to those in the ABR process with the change of influent concentration and HRT. One diluted H₂O₂ solution (various concentrations from 0.5 to 25 *mL* of the H₂O₂ solution (EMD Chemicals, Inc.) per *L* of the wastewater) was prepared and added respectively to the UV photoreactor through gravity at each flowrate. Wastewater samples at each HRT and each H₂O₂ addition were taken to measure the concentrations of TOC, TN, and COD. Two replicates of TOC, TN, and CBOD₅ concentrations were made for each sample.

The COD values of the samples taken at the flowrates of 8.8, 10.5, and 13.5 *mL/min* were not obtained due to improper dilution of the samples. Their measurements were not redone in order to reduce the experimental cost. For the same reasons, COD measurements were not made for the wastewater with the influent concentration greater than 492 *mg/L* in the UV/H₂O₂ process.

If the wastewater sample contained H₂O₂, the microorganisms would die and further CBOD₅ measurements would be affected. Therefore, catalase was required to eliminate H₂O₂ from the samples during CBOD₅ measurements. CBOD₅ measurements in the UV/H₂O₂ in the combined processes were not made due to the lack of catalase. Some CBOD₅ values of

the samples were not obtained due to the improper amount of the catalase. Their measurements were not redone because CBOD₅ sample is required to be analyzed within 24 h according to *Standard Methods* (APHA et al., 1998).

DO values of the wastewater were used to check an anaerobic condition for the ABR process. The temperature and pH of the wastewater were used as general parameters for the ABR and the UV/H₂O₂ processes. Therefore, no duplicate samples of DO, temperature, and pH were made in the measurements.

3.4 ANALYTICAL TECHNIQUES

In this study, DO, temperature, pH, TSS, VSS, TOC, TN, COD, and CBOD₅ were measured according to the following analytical techniques.

3.4.1 Dissolved Oxygen (DO)

Dissolved oxygen (DO) of the samples of influent and effluent wastewater of each compartment in the ABR were measured by a dissolved oxygen meter (YSI 58 Dissolved Oxygen Meter, YSI Inc.) equipped with a BOD bottle probe (YSI 5750 Non-Stirring BOD Bottle Probe, YSI Inc.). The DO meter was first adjusted to zero readings and then was calibrated using air-saturated water by adjusting the DO reading to a corrected calibration value. Air-saturated water was obtained by aerating water for at least 15 minutes at a constant temperature which was measured through the temperature measurement function of the DO meter. A corrected calibration value was determined using the calibration value, 99%, at Toronto's altitude (76 meters above sea level). For example, the DO value at 76 m of sea

level is 8.92 mg/L at 21°C, and then the corrected calibration value was calculated as follows.

$$\text{Corrected calibration value} = 8.92 \times 99\% = 8.47 \text{ mg/L}$$

3.4.2 Temperature and pH

Temperature and pH of the samples of influent and effluent wastewater for each compartment were measured by a Portable pH and pH/ISE Meter (230Aplus, Thermo Orion). Before use, this meter was calibrated using either pH 4.01 and 7.00 or 7.00 and 10.01 buffer solutions, depending on the expected sample range, at room temperature. During pH measurement, the temperature was displayed automatically at the same time. The measurements were done immediately at room temperature after collecting wastewater sample.

3.4.3 Total Suspended Solid (TSS) and Volatile Suspended Solid (VSS)

TSS and VSS of the anaerobic sludge and the wastewater effluent of each compartment were measured according to Sections 2540D and 2540E of *Standard Methods* (APHA *et al.*, 1998) to observe the growth of microorganisms in the ABR or to assess whether the effluent solid concentrations of the ABR reached a disposal level as shown in Table 2.3, respectively. First, Ashless Circle Whatman filter papers (Whatman International Ltd., Maidston, England) and aluminium weighing dishes were dried in an oven (Binder-World) at 103-105°C for 1 h. Five to 10 mL of well-mixed sludge samples were separately filtered by weighed filter papers using a Büchner funnel connected to a vacuum system. Then, each of the filter papers was transferred to one weighed and dried aluminium weighing dish. The combinations of dishes, sludge samples and filter papers were first heated in the oven at 103-105°C for 1 h. After

cooling in a desiccator, they were weighed, respectively. TSS was determined by Equation (3.3). A sample calculation of TSS is shown in Appendix C.

$$TSS(mg / L) = \frac{(W_1 - W_2 - W_3)}{V} \quad (3.3)$$

where W_1 is the sum of the weights of the dried filter paper, dish, and solids of sample, mg ; W_2 is the weight of dried filter paper, mg ; W_3 is the weight of dried dish, mg ; and V is the volume of sample, mL .

To determine the VSS, the combinations of dishes, sludge samples, and filter papers after drying in the oven were burned in a furnace (Box Furnace, Lindberg/Blue) at $550^{\circ}C$ for 15 minutes. After cooling in a desiccator, they were also weighed, respectively. VSS was determined by Equation (3.4). A sample calculation of VSS is shown in Appendix D.

$$VSS(mg / L) = \frac{(W_1 - W_2 - W_3) - (W_4 - W_3)}{V} = TSS - \frac{W_4 - W_3}{V} \quad (3.4)$$

where W_4 is the sum of the weights of solids of sample and dish after burning (the filter paper was burned in the furnace), mg ; and others are the same as discussed in Equation (3.3).

3.4.4 Total Organic Carbon (TOC) and Total Nitrogen (TN)

Total organic carbon (TOC) and total nitrogen (TN) were measured by an Apollo 9000 Combustion TOC Analyzer (Apollo 9000 Combustion TOC Analyzer, Teledyne Tekmar Co.) automatically. Before sample analyses, the TOC analyzer was calibrated, and the sample has to be centrifugated by a centrifuge. 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:

- 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 dessicator. For preparation of a 1,000 mg/L of KHP stock standard solution, an accurate 2,125 mg of KHP were dissolved in distilled water and was diluted to 1 L. A series of working standard solutions, covering the expected range of sample concentrations such as 1-400 mg/L, were 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 of 1-400 mg/L (Figure 3.2) was obtained for analyzing TOC concentrations. Both stock and working standard solutions were capped and stored in a 2 to 8°C refrigerator.

- Potassium nitrate (KNO₃) was used as a nitrogen source for TN calibration. Potassium nitrate was dried in the oven (Binder-World) at 80°C and cooled in the desiccator, and then 7.222 g of it were dissolved in distilled water and diluted to 1 L 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 of 1-20 mg/L (Figure 3.3) was obtained for analyzing TN concentrations.

TOC removal efficiency was determined by Equation (3.5).

$$TOC(\%) = \frac{TOC_{in} - TOC_{out}}{TOC_{in}} \times 100\% \quad (3.5)$$

where TOC_{in} is TOC concentration of influent wastewater sample, mg/L; and TOC_{out} is TOC concentration of effluent wastewater sample, mg/L.

Figure 3.2: TOC calibration curve for the range of 1-400 mgTOC/L.

Figure 3.3: TN calibration curve for the range of 1-20 mgTN/L.

3.4.5 Chemical Oxygen Demand (COD)

COD analysis was measured by prepackaged mercury-free and premixed COD vials (Bioscience Inc.) based on Section 5220 of *Standard Methods* (APHA *et al.*, 1998). Three types of COD vials with the ranges 5-150, 20-900 and 100-4,500 mgCOD/L were used in this study. One COD vial with the ranges 5-150, 20-900, and 100-4,500 mgCOD/L contained 77, 75, and 54% of sulphuric acid (H_2SO_4 , 1 mg/m³, CAS# 7664-93-9), 0.05, 0.20, and 0.14% of potassium dichromate ($\text{K}_2\text{Cr}_2\text{O}_7$, 0.0235 mg/L as Cr^{+6} , CAS# 7778-50-9), 0.40, 0.40, and 0.29% of silver sulphate (Ag_2SO_4 , 0.01 mg/m³ as Ag, CAS# 10294-26-5), 0.60, 0.60, and 0.43% of mercuric sulphate (HgSO_4 , 0.05 mg/m³ as Hg, CAS# 7783-35-9), and 0.002, 0.002, and 0.0001% of sulfamic acid ($\text{NH}_2\text{SO}_3\text{H}$, CAS# 5329-14-6), respectively.

For preparation of a 10 gCOD/L of stock standard solution, potassium hydrogen phthalate (KHP, $\text{KOCOC}_6\text{H}_4\text{COOH}$) was pre-dried to a constant weight at 110°C, and 8.5034 g of it were dissolved in distilled water and diluted to 1 L. A series of working standard solutions, covering the expected range of sample concentrations such as 100-4,500 mgCOD/L, were prepared by accurately diluting the 10 gCOD/L of stock standard solution with distilled water. Through running standard calibration analysis, a COD standard curve for the range of 100-4,500 mgCOD/L, for example, was obtained for analyzing COD concentrations.

A COD reactor (Bioscience Inc.) was preheated to 150°C before testing. A 2.5 mL sample was carefully added into one COD vial of ranges 5-150 or 20-900 mgCOD/L, and 0.5 mL sample was carefully added into one COD vial of range 100-4,500 mgCOD/L. Then the vial was thoroughly shaken by hand. COD standards and a blank (distilled water) were processed exactly the same as the samples. COD vials containing sample, COD standard, and blank,

respectively, were heated in the COD reactor for 2 h at $150\pm 2^{\circ}\text{C}$, and then they were removed from the reactor and were placed in a rack until they cooled and any suspended precipitate in the vials was settled down. After the outsides of vials were wiped to remove dusts, they were placed into a spectrophotometer (Ultrospec 1110 Pro, Biochrom Ltd.) one by one to measure their CODs under a standard curve covering the expected range of sample concentrations. The wavelength of 440, 600, and 600 nm were set for the ranges 5-150, 20-900 and 100-4,500 mgCOD/L, respectively. According to the requirements of the test method for using the COD vials (Bioscience, Inc.), blanks of the ranges 20-900 and 100-4,500 mgCOD/L were used to zero the spectrophotometer before sample testing. The highest standard (150 mg/L COD) of the range 5-150 mgCOD/L was used to zero the spectrophotometer because the standard curve of the range 5-150 mgCOD/L had a negative slope and the 150 mg/L standard would read a negative absorbance if using a blank for zeroing the spectrophotometer (the spectrophotometer cannot read negative absorbance). If samples could not be tested within 5 h of collection, they were preserved with concentrated sulphuric acid to a pH no greater than 2 and were refrigerated at 4°C until analysis.

The software, SWIFT II 1000, installed in a computer connected to the spectrophotometer was used for COD analysis. A wavelength such as 600 nm for COD range 100-4,500 mgCOD/L was first set and absorbance was zeroed by a blank. A standard curve for this COD range was generated by Run>Standards to get the absorbance readings of a series of standards with known COD concentrations. Each replicate of each standard was measured and stored, and the mean values were calculated. A standard curve (Figure 3.4) was then created using the mean absorbance values. The standard curve showed linearity between absorbance values and known standards concentrations, and was displayed in a graph view, with the results of samples superimposed upon it. An unknown COD concentration was measured by

(a)

(b)

Figure 3.4: COD standard curves for the ranges of (a) 5-150 and (b) 100-4,500 mgCOD/L, respectively.

Open>Standards, and then Run>Samples. Samples were only run after the standard curve was created. Each replicate of a sample was measured and compared with the standard curve. Each sample's result was displayed as it was collected. The COD removal efficiency was determined by Equation (3.6).

$$COD(\%) = \frac{COD_{in} - COD_{out}}{COD_{in}} \times 100\% \quad (3.6)$$

where COD_{in} is COD concentration of influent wastewater sample, mg/L ; and COD_{out} is COD concentration of effluent wastewater sample, mg/L .

3.4.6 5-Day Carbonaceous Biochemical Oxygen Demand (CBOD₅)

The analysis of the 5-day carbonaceous biochemical oxygen demand (CBOD₅) was carried out according to Section 5210B of *Standard Methods* (APHA *et al.*, 1998). A solution, which is called 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 CBOD₅ testing include acid and alkali solutions, nitrification inhibitor, and glucose-glutamic acid solution. The solutions of phosphate buffer, magnesium sulfate, calcium chloride, and ferric chloride were prepared as follows and stored in a refrigerator at 4°C after preparation.

- Phosphate buffer: 8.5 g KH₂PO₄, 21.75 g K₂HPO₄, 33.4 g Na₂HPO₄·7H₂O, and 1.7 g NH₄Cl were dissolved in 500 mL of distilled water and were diluted to 1 L. The pH was adjusted to 7.2 using 1 N sulfuric acid or 1 N sodium hydroxide solution.
- Magnesium sulfate solution: 22.5 g MgSO₄·7H₂O were dissolved in distilled water and was diluted to 1 L.
- Calcium chloride solution: 27.5 g CaCl₂ were dissolved in distilled water and was diluted

to 1 L.

- Ferric chloride solution: 0.25 g $\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$ were dissolved in distilled water and was diluted to 1 L. Each BOD bottle added 0.16 g of nitrification inhibitor.
- Nitrification inhibitor: 2-chloro-6-(trichloromethyl) pyridine (Hach Co., Formula 2533).
- 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 were diluted to 1 L. Because the BOD test is a bioassay and its results can be greatly influenced by the presence of toxicants or by use of a poor seeding material. Distilled waters frequently are contaminated with copper. Therefore, it is necessary to periodically check dilution water quality, seed effectiveness, and analytical technique. Glucose-glutamic acid standard (GGA) is used to achieve this work. The GGA solution is prepared fresh immediately before use.

Ten liters dilution water was prepared each time by the following way: 1 mL of each phosphate buffer, magnesium sulfate, calcium chloride, and ferric chloride per L of distilled water was added in a 20 L container. Then, dilution water was placed in an incubator (C25KC Classic Incubator Shaker, New Brunswick Scientific Co.) 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 (PolySeed®, InterLab® Supply) was added into 500 mL distilled water to prepare polyseed solution, which was aerated by pure air for 30 minutes and then settled for 15 minutes before use.

Three to 6 mL of one sample of the synthetic wastewater, 2 mL aerated polyseed solution, and 0.16 g nitrification inhibitor were added into one well-cleaned 300-mL BOD bottle. All

samples of the synthetic wastewater were processed exactly the same. Two blanks were prepared by filling with aerated dilution water to roughly check the quality of unseeded dilution water and the cleanliness of the BOD bottles. Three seed controls were 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 was used to stir the solution in the BOD bottle to make it homogenous during BOD₅ measurement, was placed in each bottle and then all BOD bottle 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 (YSI 5750 Non-Stirring BOD Bottle Probe, YSI Inc.) 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 CBOD₅ were calculated. A sample calculation is shown in Appendix D. CBOD₅ removal efficiency was determined by Equation (3.7).

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

where $CBOD_{5,in}$ is CBOD₅ concentration of influent wastewater sample, mg/L; and $CBOD_{5,out}$ is CBOD₅ concentration of effluent wastewater sample, mg/L.

3.4.7 Reynolds Number

The Reynolds number is defined as a number of different situations where a fluid is in relative motion to a surface (<http://en.wikipedia.org>). For flow in a pipe or tube, experimental

observations show that for fully developed flow, laminar flow occurs when $Re < 2300$, turbulent flow occurs when $Re > 4000$, and transient flow occurs when $2300 < Re < 4000$. For flow in a pipe or tube and in a rectangular duct, the Reynolds number is determined by Equation (3.8).

$$Re = \frac{\rho u L}{\mu} = \frac{\rho Q L}{\mu a} \quad (3.8)$$

Where:

- Re is Reynolds number (dimensionless);
- u is the mean fluid velocity, m/s ;
- L is a characteristic length that the flow is going through or around, m ; for a pipe or a tube, L equals to the diameter of the pipe or tube; for a rectangular duct, L equals to the hydraulic diameter of the rectangular duct, which is 4 times the cross-sectional area divided by the wetted perimeter;
- μ is the dynamic viscosity of the fluid, $kg/m.s$, for water at $25^\circ C$, $\mu = 8.98 \times 10^{-4} kg/m.s$;
- ρ is the density of the fluid, kg/m^3 , for water at $25^\circ C$, $\rho = 1000 kg/m^3$;
- Q is the volumetric flow rate, m^3/s ; and
- a is the pipe cross-sectional area, m^2 .

In this study, the ranges of the Reynolds numbers in the ABR process, the UV/H₂O₂ process alone, and the UV/H₂O₂ of combined processes were determined to be 0.9-4.1, 3.9-19.3, and 2.7-11.9, respectively, which indicated that the flows for all processes were laminar. The sample calculation and results are shown in Appendix E.

CHAPTER 4

RESULTS AND DISCUSSION

After achieving the acclimatization of the anaerobic sludge, the results obtained from various experiments for the treatment of a synthetic slaughterhouse wastewater, including a biological anaerobic baffled reactor (ABR) process, an advanced oxidation process (UV/H₂O₂ process), and their combination are discussed in this chapter.

4.1 ABR PROCESS FOR THE TREATMENT OF SYNTHETIC SLAUGHTHOUSE WASTEWATER

The experimental results of DO, temperature, pH values, TSS, VSS, TOC, TN, COD, and CBOD₅ in the ABR process are discussed in this section.

4.1.1 Dissolved Oxygen of Wastewater

The dissolved oxygen (DO) concentration of the raw wastewater was about 7.2 mg/L. The raw wastewater in the feed tank with a lid was continuously stirred by a recirculating pump to be homogeneous. The DO value of the influent wastewater was decreased to 0.6-1.2 mg/L due to the release of DO from the wastewater. After acclimatization, the DO values in compartments 1 to 5 were in the range of 0.5-1.4, 0.5-1.4, 0.5-1.4, 0.6-1.4, and 0.6-1.6 mg/L, respectively, which are depicted in Figure 4.1. A DO value of 1.4±0.6 mg/L was reported to provide an anaerobic zone for an integrated anaerobic-aerobic fixed-film reactor for the

treatment of slaughterhouse wastewater (Del Pozo and Diez, 2005). Therefore, this ABR process was operated under an anaerobic condition.

4.1.2 Temperature and pH

As shown in Figure 4.2, the temperature of the wastewater in all 5 compartments was similar to those of the influent wastewater. The temperature of the influent wastewater was in the range of 21.2-25.5°C, whilst the temperature of the wastewater in compartments 1 to 5 was in the range of 20.7-26.4, 20.4-25.8, 20.2-25.8, 20.2-25.5, and 20.2-25.7, respectively, which indicated a mesophilic digestion in the ABR process. The reason to cause the temperature fluctuations could be the room temperature, the temperature of distilled water used to prepare the synthetic wastewater, and energy release in the anaerobic digestion in the compartments.

As shown in Figure 4.3 for the entire experimental period, during the acclimatization of anaerobic sludge, the pH values of the wastewater in compartments 1 to 5 were in the ranges of 6.5-7.5, 6.5-7.5, 6.4-7.5, 6.4-7.5, and 6.5-7.4, respectively, whilst the pH values of the influent wastewater were in the range of 6.4-7.4, which showed little difference and also implied that the anaerobic sludge had not been acclimatized successfully. After the acclimatization, the pH values of the influent wastewater were in the range of 6.4-7.5, whilst the pH values of the wastewater in compartments 1 to 5 were in the ranges of 6.4-7.0, 6.3-7.0, 6.3-6.8, 6.4-6.7, and 6.4-6.8, respectively. This showed that the pH values of the influent wastewater were higher than those of all compartments which were gradually decreased, which may be attributed to the production of acetic acid generated in the anaerobic digestion of the synthetic wastewater under acidogenesis.

Figure 4.1: DO profile of the wastewater in the ABR process. The flowrate of wastewater in the acclimatization was 8.8 mL/min. The arrows in acclimatization represent the operation period at each wastewater concentration, and the arrows in actual experiments represent the operation period at various flowrates.

Figure 4.2: Temperature profile of the wastewater in the ABR process. The flowrate of wastewater in the acclimatization was 8.8 *mL/min*. The arrows in acclimatization represent the operation period at each wastewater concentration, and the arrows in actual experiments represent the operation period at various flowrates.

Figure 4.3: pH profile of the wastewater in the ABR process. The flowrate of wastewater in the acclimatization was 8.8 mL/min. The arrows in acclimatization represent the operation period at each wastewater concentration, and the arrows in actual experiments represent the operation period at various flowrates.

4.1.3 TSS and VSS of Sludge and Wastewater

The TSS values of the anaerobic sludge during the experimental period were presented in Figure 4.4. As shown in this figure, the TSS of the anaerobic sludge decreased from day 1 to day 4, which may be attributed to the fact that the anaerobic sludge from the municipal wastewater treatment plant was diluted by introducing the synthetic wastewater into the ABR. Because the anaerobic sludge was acclimatized by gradually increasing the wastewater concentration, the microorganisms gradually adapted to the sludge and gradually grew until they reached stabilization in the ABR. Final measurement of the TSS of the sludge was conducted at day 131, and showed that the TSS of the sludge at day 131 had no significant difference compared with that at day 60. During actual experiments, no sludge washout was observed, which indicates no occurrence of sludge bulking (usually occurs when the sludge fails to separate out from the wastewater).

As shown in Figure 4.5, the VSS of the anaerobic sludge had a similar appearance as those of the TSS from day 1 to day 4 due to the same fact. After day 4, the VSS of the sludge in all compartments increased first due to the growth of the microorganisms and then stayed in higher levels during the acclimatization. It was found that the trend of VSS of the sludge looked like to fall in the log phase and then stationary phase of the bacterial growth curve shown in Figure 2.1. Therefore, a growth of microorganisms in the ABR could be identified and the anaerobic sludge was considered ready for actual experiments. Final measurement of the VSS of the sludge was also conducted on day 131, and showed decreased values in some compartments but the system still worked effectively indicating the microorganisms in the sludge were still alive. Further study should take into account a longer acclimatization period for anaerobic sludge to investigate the growth of microorganisms in the ABR process.

Figure 4.4: TSS profile of the anaerobic sludge in the ABR process. Error bars represent sample standard deviations. The flowrate of wastewater in the acclimatization was 8.8 mL/min. The arrows in acclimatization represent the operation period at each wastewater concentration, and the arrows in actual experiments represent the operation period at various flowrates.

Figure 4.5: VSS profile of the anaerobic sludge in the ABR process. The flowrate of wastewater in the acclimatization was 8.8 mL/min. The arrows in acclimatization represent the operation period at each wastewater concentration, and the arrows in actual experiments represent the operation period at various flowrates. Error bars represent sample standard deviations.

The TSS and VSS values of the wastewater for the flowrates of 8.8, 10.5, 13.5, and 27.6 mL/min are presented in Table 4.1 and show no trends. The TSS and VSS values for the flowrate of 6.2 mL/min were not obtained because there were very little solids in the wastewater and could not be measured. The results showed that the TSS of the effluent wastewater at the flowrates of 8.8, 10.5, and 27.6 mL/min exceeded the disposal level as shown in Table 2.3. Further treatment for TSS and VSS should be considered if the treated wastewater was discharged. According to the measurement technique of TSS and VSS as discussed in Section 3.4.3, dried filter papers could highly affect the measurement results. Completely drying filter papers was required in order to get high precise TSS and VSS values.

Table 4.1: TSS and VSS profiles of the wastewater in each compartment of the ABR in the actual experiment.

Flowrate (mL/min)	<u>Compartment</u>									
	1	2	3	4	5	1	2	3	4	5
	TSS of wastewater (mg/L)					VSS of wastewater (mg/L)				
8.8	133	156	111	133	178	111	133	111	89	156
13.5	38	56	80	52	10	38	33	11	31	10
27.6	60	57	80	160	77	102	38	130	124	85

4.1.4 TOC, TN, COD, and CBOD₅

The TOC values of the wastewater in the ABR process are presented in Figure 4.6. As shown in this figure, 87.8% of the TOC was removed in compartments 1 and 2 at the flowrate of 6.2 mL/min , and the final TOC removal efficiency reached 89.9%, leading to 98.4 mg/L of

Figure 4.6: TOC profile of the wastewater in each ABR compartment at the HRT of 0.9, 1.7, 2.2, 2.7 and 3.8 days, respectively. Error bars represent sample standard deviations.

TOC effluent concentration from the influent TOC concentration of 973 *mg/L*. The same appearances of TOC changes occurred at the flowrates of 8.8, 10.5, and 13.5 *mL/min*, respectively. The TOC removal were 86.9, 86.2, and 78.3% in compartments 1 and 2 at the flowrates of 8.8, 10.5, and 13.5 *mL/min*, respectively, and the final TOC removal efficiencies reached 88.6, 87.9, and 83.5%, respectively. The results showed that the lower the flowrate was, the higher the TOC removal efficiency was. Since the entire ABR volume was not used to its full potential, the substrate driving forces in compartments 3, 4, and 5 might be low due to the high TOC removal in compartments 1 and 2, and acetogenesis could be higher in compartments 3, 4, and 5. At the highest flowrate of 27.6 *mL/min*, only 42.9% of the TOC was removed in compartments 1 and 2, and final TOC removal efficiency reached 59.4% at the flowrate of 27.6 *mL/min*. However, it was found that the trend of full potential use of the entire ABR volume could occur at a high flowrate.

As shown in Figure 4.7, the average TN change in the wastewater was no more than 1.6, 1.5, 6.8, 5.1, and 4.1% at the flowrates of 6.2, 8.8, 10.5, 13.5, and 27.6 *mL/min*, respectively. It has been reported that the nitrification was limited by DO concentrations of below 3 *mg/L* and denitrification was limited by DO concentrations of above 0.5 *mg/L* (Del Pozo and Diez, 2005). As discussed in Section 4.1.1, the range of DO values in all 5 compartments at all flowrates was 0.5-1.6 *mg/L*, leading to no occurrences of the nitrification and denitrification in this process. Therefore, the ABR process had no effect on TN removal for the synthetic slaughterhouse wastewater.

As Figure 4.8 shows, the COD values of the wastewater at flowrates of 6.2 and 27.6 *mL/min* in the ABR process show the similar appearance as the TOC. It was found that 91.5 and 53.7% of the COD were removed in compartments 1 and 2 at flowrates of 6.2 and 27.6

Figure 4.7: TN profile of the wastewater in each ABR compartment at the HRT of 0.9, 1.7, 2.2, 2.7 and 3.8 days, respectively. Error bars represent sample standard deviations.

Figure 4.8: COD profile of the wastewater in each ABR compartment at the HRT of 0.9 and 3.8 days, respectively.

mL/min, respectively, and the final COD removal efficiencies reached 97.7 and 63.9%, respectively, which further showed that the entire ABR volume was not used to its full potential at lower flowrate. The reasons might be the same as discussed in the TOC values in the ABR reactor. Similar findings of the trend of COD values in an ABR process have been reported by Kennedy and Barriault (2007) and Bell and Buckley (2003).

As shown in Figure 4.9, the CBOD₅ values of the wastewater at the flowrates of 6.2, 8.8, 10.5, 13.5, and 27.6 *mL/min* in the ABR process also show the similar appearance as the TOC and COD. 95.3, 63.2, 82.8, 70.3, and 63.3% of the CBOD₅ were removed in compartments 1 and 2 at the flowrate of 6.2, 8.8, 10.5, 13.5, and 27.6 *mL/min*, and the final CBOD₅ removal efficiencies reached 96.6, 89.5, 89.3, 85.6, and 84.7%, respectively. The results also showed that the entire ABR volume was not used to its full potential at lower flowrate such as 6.2 and 10.5 *mL/min*.

The complete profiles of TOC, TN, COD, and CBOD₅, and their removal are shown in Appendices F (Table F.1) and G (Figures G.1 to G.3), respectively. As shown in Table F.1, after the treatment of the ABR process, the ratio of CBOD₅/COD of the wastewater increased from 0.4 to 0.6 at the HRT of 3.8 *days* comparing with that it decreased from 0.5 to 0.2 at the HRT of 0.9 *days*, which indicated that the biodegradability of the effluent wastewater was enhanced at the longer HRT. The reasons may be attributed to the fact that the organic matters could be digested by the anaerobic sludge more completely at the longer HRT than that at the shorter HRT, and more nonbiodegradable intermediates might be generated at the shorter HRT. Meanwhile, the ratio of COD/TOC of the wastewater decreased from 2.4 to 0.5 at the HRT of 3.8 *days* comparing with that it had a little change from 2.2 and 2.0 at the HRT of 0.9 *days*, which indicated the more organic carbons in the synthetic slaughterhouse wastewater were removed at the longer HRT due to more complete digestion at longer HRT than that at

Figure 4.9: $CBOD_5$ profile of the wastewater in each ABR compartment at the HRT of 0.9, 1.7, 2.2, 2.7 and 3.8 days, respectively. Error bars represent sample standard deviations.

the shorter HRT. It concluded that the longer the HRT, the more TOC were removed from the wastewater, which are also shown in Figures G.1 to G.3. The COD values had not obtained at other HRT due to improper dilution of the samples as discussed before. As shown in Figures G.1 to G.3, at higher flowrate, the removal of TOC, COD, and CBOD₅ were increased gradually in all compartments of the ABR, which indicated that the ABR volume had higher possibility for full potential use at high flowrate of wastewater. Therefore, further study could take into account an ABR process with wastewater recycle stream and higher wastewater flowrates to investigate the full potential use of the ABR volume.

4.2 UV/H₂O₂ PROCESS ALONE FOR THE TREATMENT OF SYNTHETIC SLAUGHTERHOUSE WASTEWATER

The experimental results of dark experiment, temperature, pH values, TOC, TN, COD, and CBOD₅ in the UV/H₂O₂ process alone are discussed in this section.

4.2.1 Dark Experiment

The temperatures of dark experiments were in the range of 22.4-22.6°C, which were similar to the temperature of the influent wastewater. The pH values of dark experiments were in the range of 5.5-7.7, whilst the pH values of the influent wastewater were in the range of 6.0-7.4. The TOC and TN values of the wastewater in dark experiments in the UV/H₂O₂ process alone are presented in Table 4.2. It was found that the TOC values at H₂O₂ dosages of 529 and 1371 mgH₂O₂/L were decreased no more than 5%. Therefore, the effect of UV photoreactor walls on the TOC adsorption was negligible.

Table 4.2: TOC and TN values of the untreated wastewater in dark experiments in the UV/H₂O₂ process alone.

Concentration	Wastewater Sample	H ₂ O ₂ Dosage (mgH ₂ O ₂ /L)				
		<u>529</u>			<u>1371</u>	
TOC (mg/L)	Influent	968.4	492.2	156.0	492.7	157.6
	Dark	958.0	484.1	148.4	490.0	153.1
TN (mg/L)	Influent	442.4	188.7	68.7	186.0	68.1
	Dark	431.8	181.1	67.3	185.0	68.8

4.2.2. Temperature and pH

As shown in Figures 4.10, the temperatures of the ABR treated and untreated wastewater with the TOC influent concentrations of 155-157 mg/L increased from 24 to 30°C in the UV/H₂O₂ process alone due to the heat produced by the UV irradiation.

As shown in Figure 4.11, the pH values of the untreated wastewater with the TOC influent concentrations of 155-157 mg/L decreased from 6.0-6.2 to 4.6-4.8 with the increase in the HRT from 0.5 to 2.5 h in the UV/H₂O₂ process alone. This may be attributed to the production of organic acids and carbon dioxide which is a kind of acid gas and easy to dissolve in water. On the other hand, the pH values of the ABR treated wastewater with the TOC influent concentrations of 155-157 mg/L had no significant changes (from 6.8-7.4 to 7.0-7.2 at the HRT of 0.5 h to 2.5 h, respectively), which may be attributed to the fact that the organic matters in the untreated wastewater were different from those in the treated wastewater and might be easier to be oxidized to form acids and CO₂.

Figure 4.10: Temperature profile of the wastewater at various HRT with the TOC influent concentrations of 155-157 mg/L in the UV/ H_2O_2 process alone.

Figure 4.11: pH profile of the wastewater at various HRT with the TOC influent concentrations of 155-157 *mg/L* in the UV/H₂O₂ process alone.

4.2.3 TOC, TN, COD, and CBOD₅

The TOC values of the untreated wastewater with the H₂O₂ dosages of 529 and 1371 mgH₂O₂/L, which were the lowest and the highest dosages used in the combined processes, at various HRT of 0.5, 1.0, 1.5, 2.0, and 2.5 h are presented in Figure 4.12. As shown in this figure, at the H₂O₂ dosage of 1371 mgH₂O₂/L, the removal efficiencies of the TOC inlet concentration of 492.7 mg/L reached 8.4, 10.3, 13.0, 17.5, and 23.2% at the HRT of 0.5, 1.0, 1.5, 2.0, and 2.5 h; and the removal efficiencies for the TOC inlet concentration of 157.6 mg/L reached 21.5, 24.5, 42.5, 46.8, and 64.3% at the HRT of 0.5, 1.0, 1.5, 2.0, and 2.5 h, respectively. A similar appearance occurred for the TOC inlet concentrations of 968.4, 492.2, and 156.0 mg/L at the H₂O₂ dosage of 529 mg/L. At the HRT of 2.5 h, for the inlet concentrations of 492.2-492.7 mg/L, the TOC removal efficiency (23.2%) at the H₂O₂ dosage of 1371 mgH₂O₂/L was higher than that (8.4%) at the H₂O₂ dosage of 529 mgH₂O₂/L. Similarly, at the HRT of 2.5 h, for the inlet concentrations of 156.0-157.6 mg/L, the TOC removal efficiency (64.3%) at the H₂O₂ dosage of 1371 mgH₂O₂/L was also higher than that (34.5%) at the H₂O₂ dosage of 529 mgH₂O₂/L, which was the maximum TOC removal efficiency of the untreated synthetic wastewater. These results showed that (1) the longer the HRT was, the higher the removal efficiency of the TOC was; (2) the higher the H₂O₂ dosage (1371 mgH₂O₂/L) was, the more TOC was removed from the wastewater; and (3) the lower the TOC inlet concentration, the higher the removal efficiency was. The reason may be attributed to the fact that long HRT and the higher H₂O₂ dosage could increase the oxidation of TOC due to long contact and reaction time between TOC and H₂O₂.

The TN values of the untreated wastewater with the H₂O₂ dosages of 529 and 1371 mg/L at the HRT of 0.5, 1.0, 1.5, 2.0, and 2.5 h in the UV/H₂O₂ process alone are presented in

Figure 4.12: TOC profile of the untreated wastewater at various HRT in the UV/ H_2O_2 process alone. Error bars represent sample standard deviations.

Figure 4.13. The TN values of the untreated wastewater with the H_2O_2 dosages of 529 and 1371 mg/L at the HRT of 0.5, 1.0, 1.5, 2.0, and 2.5 h in the UV/ H_2O_2 process alone are presented in Figure 4.13. It was found that the average change of TN was no more than 1.7, 2.9, 4.1, 2.2, and 1.8% at the TOC inlet concentrations of 968.4, 492.2, 492.7, 156.0, and 157.6 mg/L , respectively, indicating that the UV/ H_2O_2 process alone had no significant effect on the TN removal for the synthetic slaughterhouse wastewater.

As shown in Figure 4.14, the COD values of the untreated wastewater showed the similar appearance as those of the TOC. At the H_2O_2 dosage of 1371 $\text{mgH}_2\text{O}_2/\text{L}$, the COD removal efficiencies for the wastewater with the inlet concentration of 157.6 mg/L reached 36.8, 46.5, 54.9, 59.6, and 81.9% at the HRT of 0.5, 1.0, 1.5, 2.0, and 2.5 h , respectively, which indicated that the longer the HRT was, the higher the removal efficiency of the COD was.

As shown in Figure 4.15, the CBOD_5 values of the untreated wastewater with the H_2O_2 dosages of 529 and 1371 mg/L at the HRT of 0.5, 1.0, 1.5, 2.0, and 2.5 h in the UV/ H_2O_2 process alone also show the same appearance as those of the TOC and the COD. At the H_2O_2 dosage of 1371 $\text{mgH}_2\text{O}_2/\text{L}$, the CBOD_5 removal efficiencies for the untreated wastewater with the inlet concentration of 492.7 mg/L reached 11.4, 11.4, 18.2, 25.0, and 47.7% at the HRT of 0.5, 1.0, 1.5, 2.0, and 2.5 h ; and those with the inlet concentration of 157.6 mg/L reached 40.2, 60.2, 72.3, 77.1, and 84.3% at the HRT of 0.5, 1.0, 1.5, 2.0, and 2.5 h , respectively. At the H_2O_2 dosage of 529 mg/L , the CBOD_5 removal efficiencies for the wastewater with the inlet concentration of 156.0 mg/L reached 43.5, 50.2, 50.2, 53.5, and 76.9% at the HRT of 0.5, 1.0, 1.5, 2.0, and 2.5 h , respectively. These results also indicated that the longer the HRT was, the higher the removal efficiency of the CBOD_5 was, and the lower the CBOD_5 inlet concentration, the higher the removal efficiency was.

Figure 4.13: TN profile of the untreated wastewater at various HRT in the UV/H₂O₂ process alone. Error bars represent sample standard deviations.

Figure 4.14: COD profile of the untreated wastewater at various HRT and the H_2O_2 dosages $1371 \text{ mgH}_2\text{O}_2/\text{L}$ in the UV/ H_2O_2 process alone.

Figure 4.15: $CBOD_5$ profile of the untreated wastewater at various HRT in the UV/ H_2O_2 process alone. Error bars represent sample standard deviations.

The complete profiles of TOC, TN, COD, and CBOD₅, and their removal are shown in Appendices F (Table F.2) and G (Figures G.4 to G.6), respectively. As shown in Table F.2, after the treatment of the UV/H₂O₂ process, the ratios of CBOD₅/COD of the untreated and the ABR treated wastewater with the inlet TOC concentration of 155.0-156.0 mg/L increased from 0.4 to 0.6 (the H₂O₂ dosage of 529 mg/L) and 0.3 to 0.5 (the H₂O₂ dosage of 1371 mg/L), respectively, at the HRT of 2.5 h, which indicated that the UV/H₂O₂ process could enhance the biodegradability of the wastewater. Meanwhile, their ratios of COD/TOC decreased from 2.3 to 0.6 and 1.8 to 0.9, respectively, which indicated that the UV/H₂O₂ process had an ability to remove organic carbons in the synthetic slaughterhouse wastewater. As shown in Figures G.4 to G.6, the longer the HRT was, the higher the removal efficiencies of TOC, COD, and CBOD₅ of the untreated wastewater were reached.

4.3 COMBINED PROCESSES OF ABR AND UV/H₂O₂ FOR THE TREATMENT OF SYNTHETIC SLAUGHTERHOUSE WASTEWATER

4.3.1 TOC, TN, COD, and CBOD₅

The TOC values of the wastewater with various H₂O₂ dosages in the UV/H₂O₂ process are presented in Figure 4.16. As shown in this figure, at the flowrates of 6.2, 8.8, 10.5, 13.5, and 27.6 mL/min, the TOC removal reached 89.9, 88.6, 87.9, 83.5, and 59.4% in the ABR process, and a further removal of 50.8, 89.0, 46.0, 26.4, and 16.5% in the UV/H₂O₂ process, respectively, leading to the overall TOC removal of 95.0, 98.8, 93.5, 87.8, and 66.0% in the combined processes as shown in Appendix G Figure G.7. This indicates that the treatment of TOC was improved in the combined processes. The concentrations of the ABR inlet and the lowest concentrations in the UV/H₂O₂ process were used to calculate the overall TOC

Figure 4.16: TOC profile of the ABR effluent wastewater with various H_2O_2 dosages at HRT of 49, 100, 129, 153, and 218 min, respectively, in the combined processes. Error bars represent sample standard deviations.

removal in the combined processes. The concentrations of the ABR outlet (the effluent of compartment 5) were used as the influent concentrations to calculate the TOC removal in the UV/H₂O₂ process. At the flowrate of 8.8 mL/min, half values of the ABR outlet were used as inlet concentration to calculate the TOC removal efficiency in the UV/H₂O₂ process because the ABR outlet was diluted by half by the H₂O₂ solution through using the same flowrate as that of the wastewater (not occurred in other wastewater flowrates where the flowrate of H₂O₂ was 0.6 mL/min).

Also as shown in Figure 4.16, the TOC was decreased first and then increased with the increase of H₂O₂ dosage in the UV/H₂O₂ process, which was attributed to the fact that H₂O₂ acts as both an oxidant and a radical scavenger (Glaze *et al.*, 1987; Stefan *et al.*, 1996), especially at high dosages, and excessive H₂O₂ reacts with hydroxyl radical, [•]OH, competing with organic compounds and consequently reducing their removal efficiencies (Rodriguez *et al.*, 2005; Varatharajan and Kanmani, 2007). The H₂O₂ dosages of 529, 602, 720, 1122, and 1371 mg/L in the combined processes were found to result in maximum TOC removal for the flowrates of 27.6, 13.5, 10.5, 8.8 and 6.2 mL/min, respectively, which indicates that more H₂O₂ is required to oxidize more TOC in the wastewater caused by low flowrate.

As discussed in Section 4.1.4 and 4.2.3, the TN of the wastewater had no significant changes in the ABR and UV/H₂O₂ processes. To be compared, the TN was also measured in the combined processes. The TN values of the synthetic wastewater in the UV/H₂O₂ process are presented in Figure 4.17. It showed that the TN had not significant changes at the flowrates of 6.2, 10.5, 13.5, and 27.6 mL/min. The average changes of the TN had no more than 14.1, 11.4, 6.2, and 2.7% at the flowrates of 6.2, 10.5, 13.5, and 27.6 mL/min, respectively, indicating that the lower the flowrate was, the more the TN changes, which may

Figure 4.17: TN profile of the ABR effluent wastewater with various H₂O₂ dosages at the HRT of 49, 100, 129, 153, and 218 min, respectively, in the combined processes. Error bars represent sample standard deviations.

be attributed the fact that the organic matters in the wastewater had long contact time with UV/H₂O₂ at lower flowrate leading to more changes of TN. At the flowrate of 8.8 mL/min, the average change of TN was about 47.0% which may be attributed to the fact that the ABR effluent was diluted by the H₂O₂ solution which had the similar flowrate (8.8 mL/min) to that of the wastewater. The results showed that the combined processes had no significant effect on the TN removal. Further study may be carried out to investigate the effect of pH on the TN degradation.

COD removal efficiencies of the wastewater in the combined processes at the flowrate of 27.6 mL/min with various H₂O₂ dosages are presented in Figure 4.18. As shown in this figure, the COD was also decreased first and then increased with the increase of H₂O₂ dosage in the UV/H₂O₂ process due to the same reason as discussed in the TOC values. H₂O₂ dosage of 529 mg/L, similar to the result in maximum TOC removal at the same flowrate, was found to result in a maximum COD removal of 65.5%. The COD at other flowrates were not obtained due to improper dilution of the COD samples.

To compare the combined processes and the UV/H₂O₂ process alone, the ABR treated wastewater with 155.0-157.6 mg/L of TOC influent concentration was prepared. The TOC values of the ABR treated and untreated wastewater at the H₂O₂ dosages of 529 and 1371 mgH₂O₂/L at the HRT of 0.5, 1.0, 1.5, 2.0, and 2.5 h in the UV/H₂O₂ process are presented in Figure 4.19. As shown, for both the ABR treated and untreated wastewater, the longer the HRT was, the more TOC was removed. It was found that at the H₂O₂ dosage of 529 mg/L, the highest TOC removal efficiencies of the ABR treated and untreated wastewater reached 36.2 and 34.5% at the HRT of 2.5 h, respectively. Also, at the H₂O₂ dosage of 1371 mg/L, the highest TOC removal efficiencies of the ABR treated and untreated wastewater reached 37.3

Figure 4.18: COD removal efficiencies of the wastewater at a flowrate of 27.6 mL/min for various H₂O₂ dosages in the combined processes.

Figure 4.19: TOC profile of the ABR treated or untreated wastewater at the H₂O₂ dosages of 529 and 1371 mg/L and various HRT in the UV/H₂O₂ process. Error bars represent sample standard deviations.

and 64.3% at the HRT of 2.5 *h*, respectively. The results showed that (1) higher H₂O₂ dosage had higher effect on the TOC removal, and (2) the UV/H₂O₂ process had higher effect on the TOC removal in the untreated wastewater, which may be attributed to the intermediates generated in the ABR process. Further study may take into account higher H₂O₂ dosages and longer HRT for the TOC removal.

The CBOD₅ values of the ABR treated and untreated wastewaters which had the similar TOC concentration (155.0-157.6 *mg/L*) in the UV process are compared in Figure 4.20. As shown, the ABR treated wastewater had lower CBOD₅ concentration (96.0 *mg/L*) than that of the untreated wastewater (124.5 *mg/L*) due to some of CBOD₅ had been removed from the ABR process. It was found that at the H₂O₂ dosage of 1371 *mg/L*, the removal efficiency of the untreated wastewater (84.3%) was higher than that of the ABR treated wastewater (53.1%) at the HRT of 2.5 *h*, which showed that the UV/H₂O₂ process had significant effect on the CBOD₅ removal in the untreated wastewater. Similar findings were obtained in the removal of TOC and the COD in the untreated wastewater.

The complete profiles of TOC and TN of the synthetic wastewater in the combined processes are shown in Appendices F (Table F.3) and G (Figures G.7 to G.10). As shown in Figure G.7, the lower the flowrate was, the higher the overall TOC removal efficiency was achieved except for the flowrate of 8.8 *mL/min*. As shown in Figures G.8 to G.10, the removal efficiencies of TOC, COD, and CBOD₅ of the untreated wastewater were higher than those of the treated wastewater, indicating that the UV/H₂O₂ process had more effect on the untreated wastewater, which may be attributed to the fact that the final organic products and intermediates generated in the ABR process might be more difficult to be oxidized by UV/H₂O₂ than the untreated wastewater.

Figure 4.20: CBOD₅ profile of the ABR treated or untreated wastewater at the H₂O₂ dosage of 1371 mg/L and various HRT in the UV/H₂O₂ process. Error bars represent sample standard deviations.

4.4 OPTIMUM H_2O_2 DOSAGES FOR THE UV/ H_2O_2 PROCESS

As shown in Figure 4.12, the H_2O_2 dosage of $1371 \text{ mgH}_2\text{O}_2/\text{L}$ for the TOC influent of 157.6 mg/L in the UV/ H_2O_2 process was found to result in a maximum TOC removal at the HRT of 0.5, 1.0, 1.5, 2.0, and 2.5 h, respectively. As shown in Figure 4.16, the H_2O_2 dosages of 529, 720, and $1371 \text{ mgH}_2\text{O}_2/\text{L}$ for the TOC influents of 385.4, 117.4, and 98.4 mg/L in the UV/ H_2O_2 of the combined processes were found to result in maximum TOC removal for the HRT of 0.9, 2.2, and 3.8 days, respectively. Therefore, the ratios of H_2O_2 concentration by TOC influent concentration and HRT of these findings are depicted in Figure 4.21. As shown in this figure, an optimum ratio of $3.5 (\text{mgH}_2\text{O}_2/\text{L})/(\text{mgTOC}_{\text{in}}/\text{L.h})$ was found to result a maximum TOC removal of 64.9% in the UV/ H_2O_2 process.

To evaluate the optimum H_2O_2 ratio of $3.5 (\text{mgH}_2\text{O}_2/\text{L})/(\text{mgTOC}_{\text{in}}/\text{L.h})$, the experiments at the flowrates of 6.2, 10.5, and 13.5 mL/min , respectively, were replicated in the UV/ H_2O_2 process. The influent TOC concentrations of the experiments were prepared to be 100.1, 120.6, and 99.3 mg/L at the flowrates of 6.2, 10.5, and 13.5 mL/min based on the TOC outlet concentrations at these flowrates (98.4 , 117.4 and 110.9 mg/L), respectively. Therefore, the H_2O_2 dosages used in the replicated experiments were determined to be 1250, 880, and 647 mg/L at the flowrates of 6.2, 10.5, and 13.5 mL/min , respectively. The comparison of TOC removal efficiencies between the previous experimental findings and the replicated experimental findings obtained by using the optimum H_2O_2 dosages is presented in Table 4.3.

As shown in this table, the TOC removals (64.0, 63.5, and 60.1%) of the replicated experiments were higher than those of previous experiments (50.8, 46.0, and 26.4%) at the flowrates of 6.2, 10.5, and 13.5 mL/min , respectively, where all were closed to the highest

Figure 4.21: TOC removal efficiencies of the wastewater vs. the ratios of H_2O_2 concentration by influent TOC concentration and HRT in the UV/ H_2O_2 process. The optimum ratio of H_2O_2 concentration by influent TOC concentration by HRT found to be $3.5 (mgH_2O_2/L)/(mgTOC_{in}/L.h)$.

Table 4.3: Comparison of TOC removals between the experimental values and the replicated experimental values obtained by using the optimum H_2O_2 dosages in the UV/ H_2O_2 process

Flowrate (mL/min)	HRT (h)	TOC Inlet in Replicated Experiment (mg/L)	H_2O_2 Dosage in Replicated Experiment (mg/L)	H_2O_2 Dosage in Previous Experiment (mg/L)	TOC Outlet in Replicated Experiment (mg/L)	TOC Removal in Previous Experiment (%)	TOC Removal in Replicated Experiment (%)
6.2	3.8	100.1	1250	1371	36.1	50.8	64.0
10.5	2.2	120.6	880	720	44.0	46.0	63.5
13.5	1.7	99.3	647	602	39.6	26.4	60.1

TOC removal in the previous experiments (64.9%). The result further demonstrated that the longer the HRT was, the higher the TOC removal efficiency was. It is concluded that the optimum H_2O_2 ratio of $3.5 (mgH_2O_2/L)/(mgTOC_{in}/L.h)$ could be used as a reference for the design of a UV/ H_2O_2 process and further investigation of its performance.

4.5 INVESTIGATION OF MODELING AND OPTIMIZATION FOR COMBINED PROCESSES FOR THE TREATMENT OF SYNTHETIC SLAUGHTERHOUSE WASTEWATER

4.5.1 Investigation of Kinetic Modeling for the ABR Process

The combined processes of ABR and UV/ H_2O_2 without recycle were designed for the treatment of the synthetic slaughterhouse wastewater which consisted of soluble complex organic compounds as discussed in Sections 3.1 and 3.2. The synthetic wastewater and sludge were mixed by changing the wastewater flow direction through alternate downflow and upflow and passed through the anaerobic sludge layer in each compartment. The kinetic model Equation (2.18) developed by Barthakur *et al.* (1991) for substrate utilization in an anaerobic digestion took into account extracellular hydrolysis of complex substrates and used

hydrolyzed products as the limiting substrates for cell growth and substrates digestion as discussed in Section 2.2.1. Therefore, Equation (2.18) was used to evaluate the performance of the ABR process in this study.

To determine the kinetic parameters μ_m , A , K_s , and R in the model, the non-linear least-square function F (Draper and Smith, 1981), which is used to fit a set of m observations with a non-linear model in n unknown parameters ($m > n$), is established as shown in Equation (4.1) (Barthakur *et al.*, 1991; Setiadi *et al.*, 1996). A MatLab function “lsqnonlin” (Version 7.5.0 R2007b), which is designated to solve the problem of non-linear least square and requires the user-defined function to compute the vector-valued function, is used to minimize the function F through the best-fit criterion which means two sets of data are the most close to each other.

$$\frac{S_T}{S_{T0}} = \frac{(1-R)A + \frac{K_s}{S_{T0}}}{\mu_m t + A - 1} + R \quad (2.18)$$

$$F = \sum_{i=1}^n \left[\left(\frac{S_T}{S_{T0}} \right)_{i, \text{experiment}} - \left(\frac{S_T}{S_{T0}} \right)_{i, \text{prediction}} \right]^2 \quad (4.1)$$

where:

- F is represents a non-linear least square function;
- S_T is substrate effluent concentration, mg/L ;
- S_{T0} is substrate influent concentration, mg/L ;
- μ is pecific growth rate of microorganism, day^{-1} ;
- μ_m is the maximum specific growth rate of microorganism, day^{-1} ;
- t is hydraulic retention time, day^{-1} ;
- R is refractory coefficient;
- A is kinetic coefficient;

- K_s is half-saturation constant for the substrate, mg/L ; and
- n is the total number of experiment.

The influent (S_{T0}) and effluent (S_T , in compartment 5) TOC concentrations of the ABR at different HRT as shown in Figure 4.6 were used in Equations (2.18) and (4.1). Invoking MatLab function “lsqnonlin”, a set of values for parameters R , A , K_s , and μ_m were given at one set of start point which was used by “lsqnonlin” to start searching to find minimum result of Equation (4.1). The first trial of start points, ($R=0.7$, $A=0.01$, $K_s=12$, $\mu_m=2$), was adopted from Setiadi *et al.* (1996). At each searching, only one set of optimum values was obtained, which indicated that the set of optimum values was global optimum values. Four sets of start points were used for searching, leading to 4 sets of values for R , A , K_s , and μ_m , which are presented in Table 4.4. Through substituting these 4 sets of parameters into Equation (2.18) to estimate the effluent TOC concentration of the ABR process at each flowrate, the average absolute relative errors of each set of parameters between the experimental data and the predicted values gave 7.9, 6.8, 6.2, and 5.4%, respectively, as also shown in Table 4.4. The parameters R , A , K_s , and μ_m of 3.1×10^{-2} , 0.4, 2.0 mg/L , and 1.9 day^{-1} with the lowest absolute relative error (5.4%) were selected to obtain the kinetic model Equation (4.2) for the ABR process. Comparing with the parameter R of 0.7 obtained by Setiadi *et al.* (1996), the result showed that the synthetic slaughterhouse wastewater used in this study had higher hydrolysable substrate due to the very low refractory coefficient (3.1×10^{-2}), indicating that the wastewater was biodegradable, which agreed with the experimental measurement of the ratio of CBOD₅/COD (0.4-0.5).

$$\frac{S_T}{S_{T0}} = \frac{0.39 + \frac{2.0}{S_{T0}}}{1.9t - 0.6} + 3.1 \times 10^{-2} \quad (4.2)$$

where all parameters are the same as described before.

Table 4.4: Parameter values affected by start point for searching optimum values of R , A , K_s ,

μ_m in Equation (2.18)

Parameter after searching	Start point selected (R , A , K_s , μ_m)			
	(0.5,1,1,1)	(0.7,0.01,12,2)	(0.5,0.1,5,2)	(0.5,0.1,2,2)
R	1.0×10^{-2}	3.4×10^{-2}	4.1×10^{-2}	3.1×10^{-2}
A	0.5	0.4	0.4	0.4
K_s	1.0	12.0	5.0	2.0
μ_m	2.1	2.0	1.9	1.9
Average relative error between S_5 and $S_{5, \text{prediction}}$ (%)	7.9	6.8	6.2	5.4

The comparison between predicted values and the experimental data at the flowrates of 6.2, 8.8, 10.5, 13.5, and 27.6 mL/min, respectively, are presented in Figure 4.22, which shows an agreement between the predicted model values and the experiment data, and implies the Equation (4.2) could be used to predict the effluent TOC concentration at a specific HRT in the ABR process. The MatLab code for function “lsqnonlin” is shown in Appendix H.

4.5.2 Investigation of Optimization for Total Electricity Cost and Hydraulic Retention Time for the ABR Process

Hydraulic retention time (HRT) is an important parameter for a wastewater treatment system, which will largely affect the final removal efficiency of organic pollutants in wastewater and the total costs of operating and maintenance (O&M) for the treatment system. It is necessary to optimize the total HRT of the treatment system. In a laboratory scale, the consumption of electricity and chemicals is a major part of O&M costs. Therefore, only electricity cost and cost of H_2O_2 consumption per mass of TOC removed were considered in the optimization of the total O&M costs of the combined processes in this study.

Figure 4.22: Comparison of the predicted values using Equation (4.2) and the experimental data of the wastewater in the ABR process.

The cost of electricity per mass of TOC removed in a continuous system was estimated by Equation (4.3), which was defined for high TOC influent concentration because the reaction rate of TOC was directly proportional to the rate of electricity use (Bolton *et al.*, 2001). Therefore, the electricity cost of the ABR is presented in Equation (4.4).

$$F_{Elec} = P_{power} \left(\frac{1000pt}{V(C_i - C_e)} \right) \quad (4.3)$$

$$F_{ABRElec} = P_{power} \left(\frac{1000p_{ABR}t_{ABR}}{V_{ABR}(C_{TOC,i} - C_{TOC,e})} \right) \quad (4.4)$$

where:

- F_{Elec} is electricity cost, \$/kg;
- P_{power} is the price of power, \$/kWh;
- p is the power rating for the system, W ;
- t is retention time, h ;
- V is the total volume of wastewater treated in time t , L ;
- C_i is the influent concentration, mg/L ;
- C_e is the effluent concentration, mg/L ;
- $F_{ABRElec}$ is the electricity cost of the ABR process \$/kg;
- p_{ABR} is the power rating of the ABR process, W , which is 80 W in this study;
- t_{ABR} is the retention time of the ABR process, h ;
- V_{ABR} is the volume of the ABR reactor, L ;
- $C_{TOC,i}$ is the TOC influent concentration of the ABR process, mg/L ; and
- $C_{TOC,e}$ is the TOC effluent concentration of the ABR process, mg/L ;

The effluent concentrations of TOC in the ABR could be predicted by Equation (4.2).

The marketing price of the electricity in Ontario according to Energy Information

Administration (2008) was \$0.055 /KWh. The calculated values of the electricity costs per mass of TOC removed for the ABR using Equations (4.2) and (4.4) with the assumption of 1000 mg/L influent TOC concentration for the ABR process are presented in Table 4.5. The total electricity costs per mass of TOC removed for the ABR are depicted in Figures 4.23.

As shown in Table 4.5 and Figure 4.23, the minimum total electricity cost of the ABR process was \$4.55 /kg of TOC removed at the HRT of 21 h, leading to 397.7 mg/L of effluent TOC concentration from the ABR process. After this HRT, it was observed that the total electricity cost of the ABR process was increased with the increase of the HRT, leading to a low effluent TOC concentration. According to disposal level for meat processing in Canada shown in Table 2.3, the effluent COD concentration of wastewater is regulated to be no greater than 250 mg/L. As discussed before, the ratio of COD/TOC of the synthetic wastewater was around 2.2-2.4, leading to about 104.2-114.6 mg/L of the TOC disposal level for the synthetic wastewater. Obviously, the TOC effluent concentrations of the ABR process (397.7 mg/L) at the HRT of 21 h with the minimum electricity cost exceeded this disposal level (104.2-114.6 mg/L).

In order to determine the optimum HRT of the ABR process under the TOC disposal level, optimization scheme for the ABR was established and solved. The influent TOC concentration of the wastewater was assumed to be 1000 mg/L. Therefore, the effluent TOC of the ABR should not exceed 1000 mg/L. By solving the inequality (4.5), the smallest retention time of the ABR process should be 0.53 days or 12.7 h. Therefore, the optimization scheme of the ABR process is presented in Equations (4.6) and (4.7).

Table 4.5: Electricity cost per mass TOC removed for the ABR process

t_{ABR} (h)	ABR inlet (mg/L)	ABR outlet (mg/L)	ABR Electricity (\$/kg)
13	1000	938.8	27.74
14	1000	797.4	9.02
15	1000	694.1	6.40
16	1000	615.4	5.43
17	1000	553.4	4.97
18	1000	503.2	4.73
19	1000	461.9	4.61
20	1000	427.2	4.56
21	1000	397.7	4.55
22	1000	372.3	4.58
23	1000	350.1	4.62
24	1000	330.7	4.68
25	1000	313.5	4.75
26	1000	298.2	4.84
27	1000	284.4	4.93
28	1000	272.0	5.02
29	1000	260.7	5.12
30	1000	250.5	5.23
31	1000	241.1	5.33
32	1000	232.5	5.44
33	1000	224.6	5.56
34	1000	217.3	5.67
35	1000	210.5	5.79
36	1000	204.2	5.91
37	1000	198.3	6.03
38	1000	192.8	6.15
39	1000	187.6	6.27
40	1000	182.8	6.39
41	1000	178.3	6.51
42	1000	174.0	6.64
43	1000	169.9	6.76
44	1000	166.1	6.89
45	1000	162.5	7.02
46	1000	159.1	7.14
47	1000	155.8	7.27
48	1000	152.8	7.40
49	1000	149.8	7.52
50	1000	147.0	7.65

Figure 4.23: Total electricity costs per mass of TOC removed in the ABR process. The influent TOC concentration was assumed to be 1000 mgTOC/L.

$$\frac{S_T}{S_{T0}} = \left(\frac{0.39 + \frac{2.0}{S_{T0}}}{1.9t - 0.6} + 3.1 \times 10^{-2} \right) = \frac{C_{TOC,e}}{C_{TOC,i}} = \left(\frac{0.39 + \frac{2.0}{C_{TOC,i}}}{1.9t - 0.6} + 3.1 \times 10^{-2} \right) \leq 1$$

$$\text{where } C_{TOC,i} = 1000 \text{ mg/L} \quad (4.5)$$

Objective function for the ABR process:

$$\text{Minimize: } F_{TotalElec} = F_{power} \left(\frac{1000 p_{ABR} t_{ABR}}{V_{ABR} (C_{TOC,i} - C_{TOC,e})} \right) \quad (4.6)$$

$$\text{Subject to:} \quad (4.7)$$

$$\frac{S_T}{S_{T0}} = \left(\frac{0.39 + \frac{2.0}{S_{T0}}}{1.9t - 0.6} + 3.1 \times 10^{-2} \right) = \frac{C_{TOC,e}}{C_{TOC,i}} = \left(\frac{0.39 + \frac{2.0}{C_{TOC,i}}}{1.9t_{ABR}/24 - 0.6} + 3.1 \times 10^{-2} \right) \quad (4.2)$$

$$t_{ABR} \geq 12.7$$

$$C_{TOC,e} < C_{TOC,i} = 1000$$

$$C_{TOC,e} \leq 100$$

$$C_{TOC,i}, C_{TOC,e} \geq 0$$

where all parameters are the same as described before.

The MatLab function “fmincon”, which is designated to solve the minimum of a constrained nonlinear multivariable function, is a gradient-based method that is designed to work on problems where the objective and constraint functions are both continuous and have continuous first derivatives. It attempts to find a constrained minimum of a scalar function of several variables starting at an initial estimate through a line searching and uses a sequential quadratic programming (SQP) method.

Setting 100 mg/L as a restriction for TOC effluent for the ABR process and using the

function "fmincon" to solve Equations (4.6) and (4.7), the optimum HRT and the minimum electricity cost of the ABR process alone were determined to be 78.9 h and \$11.45 /kg of TOC removed, respectively, giving 100.0 mgTOC/L of the effluent concentration which met the TOC disposal level. The results showed that the optimum HRT corresponding to the minimum electricity consumption of the process depends on the restriction of the TOC effluent concentration. Matlab code of function "fmincon" is shown in Appendix I.

At lab scale, the total O&M costs consist of the total electricity costs and the cost of chemical consumption per mass of TOC removed. Therefore, the total O&M costs of the ABR process were the total electricity cost, which was \$11.44 /kg of TOC removed.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

A biological anaerobic baffled reactor (ABR), an UV/H₂O₂ process, and their combination were developed at laboratory scale for the treatment of a synthetic slaughterhouse wastewater in this study. The performance and the treatment ability of the ABR process, the UV/H₂O₂ process, and their combination for the treatment of the synthetic wastewater were identified through the measurements of the removal efficiencies of TOC, COD, and CBOD₅. The ratio of CBOD₅/COD of the untreated synthetic wastewater was about 0.4-0.5, which indicated the synthetic wastewater was biodegradable, whilst the ratio of COD/TOC was about 2.2-2.4.

The ABR process had high treatment ability for the untreated synthetic wastewater. The removal efficiencies of TOC, COD, and CBOD₅ of the wastewater with an influent concentration of 973 mgTOC/L and a HRT of 3.8 days reached 89.9, 97.7, and 96.6%, respectively. The longer the hydraulic retention time was, the higher the removal efficiency of the wastewater was. Most of organic pollutants were removed in the first and second compartments in the ABR. After the treatment of the ABR process, the ratio of CBOD₅/COD of the wastewater changed from 0.4 to 0.6 at the HRT of 3.8 days and 0.5 to 0.2 at the HRT of 0.9 days indicating that the biodegradability of the wastewater was enhanced after longer HRT, whilst the ratio of COD/TOC of the wastewater decreased from 2.4 to 0.5 at the HRT of 3.8 days comparing with that it had a little change from 2.2 to 2.0 at the HRT of 0.9 days,

indicating that more organic carbons in the synthetic slaughterhouse wastewater were removed after the longer HRT.

The UV/H₂O₂ process had lower treatment ability than that of the ABR process. The removal efficiencies of TOC, COD, and CBOD₅ of the untreated wastewater with an influent concentration of 158 mgTOC/L, a HRT of 2.5 h and a H₂O₂ dosage of 1371 mgH₂O₂/L reached 64.9, 81.9, and 84.3%, respectively. The higher the H₂O₂ dosage or the longer the HRT were, the higher the removal efficiency was achieved. After mixing with H₂O₂ solution, the ratio of CBOD₅/COD of the synthetic wastewater was about 0.3-0.4. After the treatment of the UV/H₂O₂ process, the ratios of CBOD₅/COD of the untreated and the ABR treated wastewater increased from 0.4 to 0.6 and 0.3 to 0.5 at the HRT of 2.5 h, respectively, indicating that the UV/H₂O₂ process had the ability to enhance the biodegradability of the effluent wastewater. Meanwhile, the ratios of COD/TOC of the wastewater decreased from 2.3 to 0.6 and 1.8 to 0.9, respectively, indicating that the UV/H₂O₂ process had an ability to remove organic carbons in the synthetic slaughterhouse wastewater.

The combined processes of ABR and UV/H₂O₂ were proved to be able to improve the treatment ability of the TOC of the synthetic wastewater. The overall TOC removal efficiency of the wastewater with an influent concentration of 973 mgTOC/L reached 95.0% (89.9% in the ABR and 50.8% in the UV/H₂O₂ process) at HRT of 3.8 days for the ABR process and 3.6 h for the UV/H₂O₂ process with 1371 mgH₂O₂/L of H₂O₂. An optimum ratio of H₂O₂ concentration by TOC influent concentration and HRT was found to be 3.5 (mgH₂O₂/L)/(mgTOC_{in}/L.h).

No significant changes of the total nitrogen were observed in all processes including the

ABR process, the UV/H₂O₂ process, and their combination, which may be attributed to the fact that the nitrification and denitrification could not occur in an anaerobic condition.

A kinetic model was investigated for the ABR process to evaluate the effluent TOC concentrations of the wastewater at a specified HRT in steady-state conditions. Based on the experimental data, the parameters of the kinetic model for the ABR process were determined to be 3.1×10^{-2} for refractory coefficient, 0.4 for kinetic coefficient, 2.0 mg/L for half-saturation constant for hydrolyzed substrate, and 1.9 day⁻¹ for the maximum specific growth rate of organism, respectively. The kinetic model gave an agreement between the predicted values and the experimental data.

An optimization scheme for the ABR process involving the kinetic model for the ABR process was established and solved with the assumption of 1000 mg/L of influent TOC concentration and no greater than 100 mg/L of effluent TOC concentration of the synthetic wastewater, respectively. The optimum total HRT and the minimum electricity cost of the ABR process were determined to be 78.9 h and \$11.45 /kg of TOC removed, respectively, giving 100.0 mgTOC/L of the effluent concentration.

5.2 RECOMMENDATIONS

- Further study should take into account a longer acclimatization period for anaerobic sludge to investigate the growth of microorganisms in the ABR process.
- Further study could take into account wastewater recycle stream and high wastewater flowrates in the ABR process to investigate the full potential use of the ABR volume.
- The accumulation of volatile fatty acids and the collection of biogas in each

compartment of the ABR could be taken into account to investigate the activities of acidogenesis and methanogenesis there.

- Further study may take into account higher H_2O_2 dosages and longer HRT to investigate the high treatment ability of the UV/ H_2O_2 process.
- Further experiments could take into account the effect of pH and alkalinity on the treatment of TOC and TN in the synthetic wastewater in the UV/ H_2O_2 process.
- Further study could take into account process redesign for total nitrogen removal.
- Actual slaughterhouse wastewater could be used in the combined processes to evaluate its experimental findings and the possibility of application in practice.

REFERENCES

- J.C. Akunna, M. Clark. (2000). Performance of a granular-bed anaerobic baffled reactor (GRABBR) treating whisky distillery wastewater. *Bioresource Technology*, 74, 257-261.
- N.Z. Al-Mutairi, M. F. Hamoda, I. A. Al-Ghusain. (2003). Performance-based characterization of a contact stabilization process for slaughterhouse wastewater. *Journal of Environmental Science and Health-Part A-Toxic/Hazardous Substances & Environmental Engineering*, A38(10), 2287-2300.
- N.Z. Al-Mutairi, M.F. Hamoda, I.A. Al-Ghusain. (2004). Coagulant selection and sludge conditioning in a slaughterhouse wastewater treatment plant. *Bioresource Technology*, 95(2), 115-119.
- APHA (American Public Health Associate), American Water Works Association, Water Environment Federation. (1998). *Standard Methods for the Examination of Water and Wastewater*. Washington D.C.
- T. Aye, M. Mehrvar, W.A. Anderson. (2003). Photocatalytic treatment of cibacron brilliant yellow 3G-P (reactive yellow 2 textile dye). *Journal of Environmental Science & Health, Part A: Toxic/Hazardous Substances & Environmental Engineering*, 38(9), 1903-1914.
- T. Aye, M. Mehrvar, W.A. Anderson. (2004). Effects of photocatalysis on the biodegradability of cibacron brilliant yellow 3G-P (reactive yellow 2). *Journal of Environmental Science & Health, Part A: Toxic/Hazardous Substances & Environmental Engineering*, 39(1), 113-126.
- A. Bachmann, V.L. Beard, P.L. McCarty. (1985). Performance characteristics of the anaerobic baffled reactor. *Water Research*, 19(1), 99-106.
- W.P. Barber, D.C. Stuckey. (1999). The use of the anaerobic baffled reactor (ABR) for wastewater treatment: a review. *Water Research*, 33, 1559-1578.

- A. Barthakur, M. Bora, H.D. Singh. (1991). Kinetic model for substrate utilization and methane production in the anaerobic digestion of organic feeds. *Biotechnol. Prog.*, 7(2), 369-376.
- M. Bayramoglu, M. Kobya, M. Eyvaz, E. Senturk. (2006). Technical and economic analysis of electrocoagulation for the treatment of poultry slaughterhouse wastewater. *Separation and Purification Technology*, 51, 404-408.
- J. Bell, C.A. Buckley. (2003). Treatment of a textile dye in the anaerobic baffled reactor. *ISSN 0378-4738 = WATER SA*, 29(2), 129-134.
- F.J. Beltrán, G. Ovejero, B. Acedo. (1993). Oxidation of atrazine in water by ultraviolet radiation combined with hydrogen peroxide. *Water Research*, 27, 1013-1021.
- F.J. Beltrán, J. Rivas, P.M. Álvarez, M.A. Alonso, B. Acedo. (1999). A kinetic model for advanced oxidation processes of aromatic hydrocarbons in water: application to phenanthrene and nitrobenzene. *Industrial & Engineering Chemistry Research*, 38, 4189-4199.
- M.O. Benka-Coker, O.O. Ojior. (1995). Effect of slaughterhouse wastes on the water quality of Ikpoba River, Nigeria. *Bioresource Technology*, 52(1), 5-12.
- B.H.J. Bielski, D.E. Cabell, R.L. Arudi, A.B. Ross. (1985). Reactivity of HO_2/O_2^- Radicals in Aqueous Solution. *Journal of Physical and Chemical Reference Data*, 14(4), 1041-1100.
- I. Bodík, K. Kratochvíl, E. Gašparilová, M. Hutňan. (2003). Nitrogen removal in an anaerobic baffled filter reactor with aerobic post-treatment. *Bioresource Technology*, 86, 79-84.
- L. Bolduc, W.A. Anderson. (1997). Enhancement of the biodegradability of model wastewater containing recalcitrant or inhibitory chemical compounds by photocatalytic pre-oxidation. *Biodegradation*, 8, 237-249.
- J.R. Bolton, K.G. Bircher, W. Tumas, C.A. Tolman. (2001). Figures-of-merit for the technical

- development and application of advanced oxidation technologies for both electric- and solar-driven system. *Pure and Applied Chemistry*, 73, 627-637.
- R. Boopathy, V.F. Larsen, E. Senior. (1988). Performance of anaerobic baffled reactor (ABR) in treating distillery waste water from a Scotch Whisky Factory. *Biomass*, 16, 133-143.
- R. Boopathy. (1998). Biological treatment of swine waste using anaerobic baffled reactors. *Bioresource Technology*, 64, 1-6.
- R. Borja, C.J. Banks. (1994). Performance and kinetics of an upflow anaerobic sludge blanket (UASB) reactor treating slaughterhouse wastewater. *Journal of Environmental Science and Health*, A29, 2063-2085.
- R. Borja, C.J. Banks, Z. Wang. (1995a). Performance of a hybrid anaerobic reactor, combining a sludge blanket and a filter, treating slaughterhouse wastewater. *Applied Microbiology and Biotechnology*, 43, 351-357.
- R. Borja, C.J. Banks, Z. Wang. (1995b). Effect of organic loading rate on anaerobic treatment of slaughterhouse wastewater in a fluidised-bed reactor. *Bioresource Technology*, 52, 157-162.
- R. Borja, C. J. Banks, Z. Wang, A. Mancha (1998). Anaerobic digestion of slaughterhouse wastewater using a combination sludge blanket and filter arrangement in a single reactor. *Bioresource Technology*, 65, 125-133.
- M.A. Bull, R.M. Sterritt, J.N. Lester. (1982). The treatment of wastewaters from the meat industry: A review. *Environmental Technology Letters*, 3, 117-126.
- G.V. Buxton, C.L. Greenstock, W.P. Helman, A.B. Ross. (1988). Critical review of rate constants for reactions of hydrated electrons, hydrogen atoms and hydroxyl radicals ($\cdot\text{OH}/\cdot\text{O}^\cdot$) in aqueous solution. *Journal of Physical and Chemical Reference Data*, 17(2), 513-886.
- D.P. Cassidy, E. Beliz. (2005). Nitrogen and phosphorus removal from an abattoir

- wastewater in a SBR with aerobic granular sludge. *Water Research*, 39, 4817-4823.
- C.P. Chávez, R.L. Castillo, L. Dendooven, E.M. Escamilla-Silva. (2005). Poultry slaughter wastewater treatment with an up-flow anaerobic sludge blanket (UASB) reactor. *Bioresource Technology*, 96, 1730-1736.
- D.E. Contois. (1959). Kinetics of bacterial growth: relationship between population density and specific growth rate of continuous cultures. *Journal of General Microbiology*, 21, 40-50.
- Correctional Service Canada. (2003). Environmental Guidelines: Management of Wastewater Treatment Systems (EG 318-6).
<http://www.csc-scc.gc.ca/text/plcy/cdshtm/318-gl6-cd-eng.shtml> (accessed on October 12, 2007).
- J.C. Crittenden, S. Hu, D.W. Hand, S.A. Green. (1999). A kinetic model for H₂O₂/UV process in a completely mixed batch reactor. *Water Research*, 33(10), 2315-2328.
- J.L. De Moraes, P.P. Zamora. (2005). Use of advanced oxidation processes to improve the biodegradability of mature landfill leachates. *Journal of Hazardous Materials*, B123, 181-186.
- R. Del Pozo, V. Diez, S. Beltrán. (2000). Anaerobic pre-treatment of slaughterhouse wastewater using fixed-film reactors. *Bioresource Technology*, 71, 143-149.
- R. Del Pozo, V. Diez. (2003). Organic matter removal in combined anaerobic-aerobic fixed-film bioreactors. *Water Research*, 37(15), 3561-3568.
- R. Del Pozo, D.O. Tas, H. Dulkadiroglu, D. Orhon, V. Diez. (2003). Biodegradability of slaughterhouse wastewater with high blood content under anaerobic and aerobic conditions. *Journal of Chemical Technology & Biotechnology*, 78(4), 384-391.
- R. Del Pozo, V. Diez. (2005). Integrated anaerobic-aerobic fixed-film reactor for slaughterhouse wastewater treatment. *Water Research*, 39, 1114-1122.

- R. Del Pozo, V. Diez, G. Salazar, J.J. Espinosa. (2006). The influence of influent distribution and blood content of slaughterhouse wastewater on the performance of anaerobic fixed-film reactor. *Journal of Chemical Technology and Biotechnology*, 81, 282-288.
- N. Draper, H. Smith. (1966). *Applied Regression Analysis*. New York: Wiley.
- W. W. Eckenfelder, Jr. (2000). *Industrial Water Pollution Control*, 3rd Ed., McGraw-Hill.
- M. Edalatmanesh, M. Mehrvar, R. Dhib. (2008). Optimization of phenol degradation in a combined photochemical-biological wastewater treatment system. *Chemical Engineering Research & Design: Transactions of the Institution of Chemical Engineers Part A*, 86(11), 1243-1252.
- M. Edalatmanesh. (2006). Phenol degradation by combined photochemical-biological wastewater treatment system: kinetic modeling and optimization. Master's thesis, Ryerson University.
- Energy Information Administration. (2008).
<http://www.eia.doe.gov/emeu/international/elecpril.html> (accessed on February 25, 2009).
- S. Esplugas, J. Giménez, S. Contreras, E. Pascual, M. Rodríguez. (2002). Comparison of different advanced oxidation processes for phenol degradation. *Water Research*, 36, 1034-1042.
- L. Fang. (2000). Environmental effects of the beef industry. *Agricultural and Natural Resource Economics Discussion Paper 4/00*.
- J.A. Fiestas, A. Martín, R. Borja. (1990). Influence of immobilization supports on the kinetic constants of anaerobic purification of olive mill wastewater. *Biological Wastes*, 33, 131-142.
- K.M. Foxon, S. Pillay, T. Lalbahadur, N. Rodda, F. Holder, C.A. Buckley. (2004). The anaerobic baffled reactor (ABR): An appropriate technology for on-site sanitation. *ISSN*

- wastewater in a SBR with aerobic granular sludge. *Water Research*, 39, 4817-4823.
- C.P. Chávez, R.L. Castillo, L. Dendooven, E.M. Escamilla-Silva. (2005). Poultry slaughter wastewater treatment with an up-flow anaerobic sludge blanket (UASB) reactor. *Bioresource Technology*, 96, 1730-1736.
- D.E. Contois. (1959). Kinetics of bacterial growth: relationship between population density and specific growth rate of continuous cultures. *Journal of General Microbiology*, 21, 40-50.
- Correctional Service Canada. (2003). Environmental Guidelines: Management of Wastewater Treatment Systems (EG 318-6).
<http://www.csc-scc.gc.ca/text/plcy/cdshtm/318-gl6-cd-eng.shtml> (accessed on October 12, 2007).
- J.C. Crittenden, S. Hu, D.W. Hand, S.A. Green. (1999). A kinetic model for H₂O₂/UV process in a completely mixed batch reactor. *Water Research*, 33(10), 2315-2328.
- J.L. De Morais, P.P. Zamora. (2005). Use of advanced oxidation processes to improve the biodegradability of mature landfill leachates. *Journal of Hazardous Materials*, B123, 181-186.
- R. Del Pozo, V. Diez, S. Beltrán. (2000). Anaerobic pre-treatment of slaughterhouse wastewater using fixed-film reactors. *Bioresource Technology*, 71, 143-149.
- R. Del Pozo, V. Diez. (2003). Organic matter removal in combined anaerobic-aerobic fixed-film bioreactors. *Water Research*, 37(15), 3561-3568.
- R. Del Pozo, D.O. Tas, H. Dulkadiroglu, D. Orhon, V. Diez. (2003). Biodegradability of slaughterhouse wastewater with high blood content under anaerobic and aerobic conditions. *Journal of Chemical Technology & Biotechnology*, 78(4), 384-391.
- R. Del Pozo, V. Diez. (2005). Integrated anaerobic-aerobic fixed-film reactor for slaughterhouse wastewater treatment. *Water Research*, 39, 1114-1122.

- R. Del Pozo, V. Diez, G. Salazar, J.J. Espinosa. (2006). The influence of influent distribution and blood content of slaughterhouse wastewater on the performance of anaerobic fixed-film reactor. *Journal of Chemical Technology and Biotechnology*, 81, 282-288.
- N. Draper, H. Smith. (1966). *Applied Regression Analysis*. New York: Wiley.
- W. W. Eckenfelder, Jr. (2000). *Industrial Water Pollution Control*, 3rd Ed., McGraw-Hill.
- M. Edalatmanesh, M. Mehrvar, R. Dhib. (2008). Optimization of phenol degradation in a combined photochemical-biological wastewater treatment system. *Chemical Engineering Research & Design: Transactions of the Institution of Chemical Engineers Part A*, 86(11), 1243-1252.
- M. Edalatmanesh. (2006). Phenol degradation by combined photochemical-biological wastewater treatment system: kinetic modeling and optimization. Master's thesis, Ryerson University.
- Energy Information Administration. (2008).
<http://www.eia.doe.gov/emeu/international/elecpril.html> (accessed on February 25, 2009).
- S. Esplugas, J. Giménez, S. Contreras, E. Pascual, M. Rodríguez. (2002). Comparison of different advanced oxidation processes for phenol degradation. *Water Research*, 36, 1034-1042.
- L. Fang. (2000). Environmental effects of the beef industry. *Agricultural and Natural Resource Economics Discussion Paper 4/00*.
- J.A. Fiestas, A. Martín, R. Borja. (1990). Influence of immobilization supports on the kinetic constants of anaerobic purification of olive mill wastewater. *Biological Wastes*, 33, 131-142.
- K.M. Foxon, S. Pillay, T. Lalbahadur, N. Rodda, F. Holder, C.A. Buckley. (2004). The anaerobic baffled reactor (ABR): An appropriate technology for on-site sanitation. *ISSN*

0378-4738 = *WATER SA*, 30(5) (Special Edition), 44-50.

- N.G. Fransen, B.A.P. Urlings, P.G.H. Bijker, J.G.V. Logtestijin. (1995). Chemical and biochemical aspect of slaughterhouse sludge intended for feed purpose. *Journal of Agriculture and Food Chemistry*, 43, 2071-2076.
- W. Fuchs, H. Binder, G. Mavrias, R. Braun (2003). Anaerobic treatment of wastewater with high organic content using a stirred tank reactor coupled with a membrane filtration unit. *Water Research*, 37, 902-908.
- A. Gadgil. (1995). UV Waterwoks 2.0: answers to 10 commonly asked questions about the design, operation, and economics. Lawrence Berkeley National Laboratory, Berkeley, CA. Retrieved from <http://eetd.lbl.gov/IEP/archive/uv/pdf/ten-faqs.pdf> (accessed on March 5, 2009).
- S. Gariépy, R. D. Tyagi, D. Couillard, F. Tran. (1989). Thermophilic process for protein recovery as an alternative to slaughterhouse wastewater treatment. *Biological Wastes*, 29(2), 93-105.
- W.H. Glaze. (1987). Drinking-water treatment with ozone. *Environmental Science and Technology*, 21, 224-230.
- A. Grobicki, D.C. Stuckey. (1991). Performance of the anaerobic baffled reactor under steady-state and shock loading conditions. *Biotechnology and Bioengineering*, 37, 344-355.
- R. Grover, S.S. Marwaha, J.F. Kennedy. (1999). Studies on the use of an anaerobic baffled reactor for the continuous anaerobic digestion of pulp and paper mill black liquors. *Process Biochemistry*, 34, 653-657.
- A. Gutiérrez-Sarabia, G. Fernández-Villagómez, P. Martínez-Pereda, N. Rinderknecht-Seijas, H.M. Poggi-Varaldo. (2004). Slaughterhouse wastewater treatment in a full-scale system with constructed wetlands. *Water Environment Research*, 76(4),

- C. Haan, H. Steinfeld, H. Blackburn. (1996). *Livestock & the Environment*, Chapter 5: Beyond production systems, Processing of livestock products. United Kingdom.
<http://www.fao.org/AG/aga/lspa/LXEHTML/tech/ch5d.htm> (accessed on October 25, 2007).
- D. Hâncu, E.J. Bechman. (2001). Generation of hydrogen peroxide directly from H₂ and O₂ using CO₂ as the solvent. *Green Chemistry*, 3(2), 80-86.
- L.W. Hulsho Pol. (1995). Waste characteristics and factors affecting reactor performance. Lecture notes by Hulsho, Pol in International Course on Anaerobic Wastewater Treatment, Wageningen Agriculture University, The Delft, Netherlands.
- M. Hutòan, L. Mrafková, M. Drtil, J. Derco. (1999). Methanogenic and Nonmethanogenic Activity of Granulated Sludge in Anaerobic Baffled Reactor. *Chemical Engineering, Papers* 53(6), 374-378.
- IFC (International Finance Corporation). (2007). Environmental, Health and Safety Guidelines for Meat Processing.
[http://www.ifc.org/ifcext/enviro.nsf/AttachmentsByTitle/gui_EHSGuidelines2007_MeatProcessing/\\$FILE/Final+-+Meat+Processing.pdf](http://www.ifc.org/ifcext/enviro.nsf/AttachmentsByTitle/gui_EHSGuidelines2007_MeatProcessing/$FILE/Final+-+Meat+Processing.pdf) (accessed on October 12, 2007).
- T. Jian, X. Zhang. (1999). Bioprocesssing for slaughterhouse wastewater and its computerized control and supervisory system. *Conservation and Recycling*, 27, 145-149.
- M.R. Johns. (1995). Developments in wastewater treatment in the meat processing industry: A review. *Bioresource Technology*, 54, 203-216.
- M.B. Johnson, M. Mehrvar. (2008). Aqueous metronidazole degradation by UV/H₂O₂ process in single- and multi- lamp tubular photoreactors: kinetics and reactor design. *Industrial & Engineering Chemistry Research*, 47, 6525-6537.
- M.B. Johnson. (2007). Modeling the advanced oxidation of the pharmaceutical compound

- metronidazole in single- and multi-lamp tubular photoreactors. Master's thesis, Ryerson University.
- K. Kennedy, M. Barriault. (2007). Treatment kinetics of aircraft deicing fluid in an anaerobic baffled reactor. *Journal of Environmental Engineering and Science*, 6, 11-17.
- M. Kobya, E. Senturk, M. Bayramoglu. (2006). Treatment of poultry slaughterhouse wastewaters by electrocoagulation. *Journal of Hazardous Materials*, 133(1-3), 172-176.
- W.H. Koppenol, J. Butler, J.W. van Leeuwen. (1978). The Haber-Weiss cycle. *Photochemistry and Photobiology*, 28, 655-658.
- Ö.S. Kusçu, D.T. Sponza. (2005). Performance of anaerobic baffled reactor (ABR) treating synthetic wastewater containing *p*-nitrophenol. *Enzyme and Microbial Technology*, 36, 888-895.
- Ö.S. Kusçu, D.T. Sponza. (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 Biochemistry*, 41, 1484-1492.
- A. Langenhoff, N. Intrachanadra, D. Stuckey. (2000). Treatment of dilute soluble and colloidal wastewater using an anaerobic baffled reactor: influence of hydraulic retention time. *Water Research*, 34(40), 1037-1317.
- H.W. Lee, G. Chen, P.L. Yue (2001). Integration of chemical and biological treatments for textile industry wastewater. *Water Science and Technology*, 44(5), 75-83.
- O. Legrini, E. Oliveros, A.M. Braun. (1993). Photochemical processes for water treatment. *Chemical Review*, 93, 671-698.
- G. Lettinga, J. Field, J. Van Lier, G. Zeeman, L.W. Hulshoff Pol. (1997). Advanced anaerobic wastewater treatment in the near future. *Water Science and Technology*, 35(10), 5-12.
- G. Lettinga, L.W. Hulshoff Pol. (1991). UASB-process design for various types of

- wastewaters. *Water Science and Technology*, 24(8), 87-107.
- N.T. Manjunath, I. Mehrotra, R.P. Mathur. (2000). Treatment of wastewater from slaughterhouse by DAF-UASB system. *Water Research*, 34(6), 1930-1936.
- U. Marchaim, D. Levanon, O. Danai, S. Musaphy. (1991). A suggested solution for slaughterhouse wastes: uses of the residual materials after anaerobic digestion. *Bioresource Technology*, 37, 127-134.
- J.C. Marconato, E. D. Bidio, M. Mallo, M. Galisteo, M. Vinas. (1998). Treatment of wastewater from a fowl slaughterhouse using cast-iron electrodes. *Bulletin of Electrochemistry*, 14(6-7), 228-230.
- D.I. Massé, L. Masse. (2000a). Characterization of wastewater from hog slaughterhouses in eastern Canada and evaluation of their in-plant wastewater treatment systems. *Canadian Agriculture Engineering*, 42(3), 139-146.
- D.I. Massé, L. Masse. (2000b). Treatment of slaughterhouse wastewater in anaerobic sequencing batch reactors. *Canadian Agriculture Engineering*, 42(3), 131-137.
- D.I. Massé, L. Masse. (2001). The effect of temperature on slaughterhouse wastewater treatment in anaerobic sequencing batch reactors. *Bioresource Technology*, 76(2), 91-98.
- Metcalf and Eddy, Inc. (1993). *Wastewater Engineering – Treatment and Reuse*, 4th Ed., McGraw-Hill.
- P.L. McCarty. (1966). Kinetics of waste assimilation in anaerobic treatment. *Development in Industrial Microbiology*, 7, American Institute of Biological Sciences, Washington DC, 144-155.
- P.L. McCarty, F.E. Mosey. (1991). Modeling of anaerobic digestion processes (a discussion of concepts). *Water Science and Technology*, 24(8), 17-33.
- M. Mehrvar, W.A. Anderson, M. Moo-Young. (2001). Photocatalytic degradation of aqueous organic solvents in the presence of hydroxyl radical scavengers. *International Journal of*

Photoenergy, 3, 187-191.

M. Mehrvar, W.A. Anderson, M. Moo-Young. (2002). Comparison of the photoactivities of two commercial titanium dioxide powders in the degradation of 1,4-dioxane.

International Journal of Photoenergy, 4, 141-146.

M. Mehrvar, G.B. Tabrizi. (2006). Combined photochemical and biological processes for the treatment of linear alkylbenzene sulfonate in water. *Journal of Environmental Science & Health, Part A: Toxic/Hazardous Substances & Environmental Engineering*, 41(4), 581-597.

M. Merzouki, N. Bernet, J.P. Delgenès, M. Benlemlih. (2005). Effect of prefermentation on denitrifying phosphorus removal in slaughterhouse wastewater. *Bioresource Technology*, 96, 1371-1322.

O.M. Millamena. (1992). Ozone treatment of slaughterhouse and laboratory wastewaters. *Aquacultural Engineering*, 11, 23-31.

L.A.S. Miranda, J.A.P. Henriques, L.O. Monteggia. (2005). A full-scale UASB reactor for treatment of pig and cattle slaughterhouse wastewater with a high oil and grease content. *Brazilian Journal of Chemical Engineering*, 22(4), 601-610.

G.S. Mittal. (2004). Characterization of the effluent wastewater from abattoirs for land application. *Food Review International*, 20(3), 229-256.

G.S. Mittal. (2006). Treatment of wastewater from abattoirs before land application – a review. *Bioresource Technology*, 97, 1119-1135.

K. Mudrak, S. Kunst. (1986). *Biology of Sewage Treatment and Water Pollution Control*. England: Ellis Horwood Ltd, 193.

N.B. Reg. 88-200.

<http://www.canlii.org/en/nb/laws/regu/nb-reg-88-200/latest/nb-reg-88-200.html> (accessed on October 12, 2007).

- E. N. Manaila, D. I. Martin, G. D. Craciun, D. I. Ighigeanu, C. I. Matei, C. V. Oproiu, N. I. Iacob, H.M. Iovu, M. I. Sandu, E. D. Vulpasu, G. I. Racoriteanu. (2005). Application of polyelectrolytes obtained by radiation processing to potable and waste water treatment. *IEEE Transaction on Industry Application*, 41(3), 698-705.
- S. Nachaiyasit, D.C. Stuchey. (1997), Effect of low temperatures on the performance of an anaerobic baffled reactor (ABR). *Journal of Chemical Technology and Biotechnology*, 69, 276-284.
- P.H. Nhat (2006). Environmental performance improvement for small and medium-sized slaughterhouses in Vietnam. *Environmental, Development and Sustainability*, 8, 251-269.
- L.A. Núñez, B. Martínez. (1999). Anaerobic treatment of slaughterhouse wastewater in an expanded granular sludge bed (EGSB) reactor. *Water Science and Technology*, 40(8), 99-106.
- L.A. Núñez, E. Fuente, B. Martínez, P.A. García. (1999). Slaughterhouse wastewater treatment using ferric and aluminum salts and organic polyelectrolites. *Journal of Environmental Science and Health*, A34(3), 721-736.
- S.J. Pirt. (1975). *Principles of microbe and cell cultivation*. Blackwell Scientific Publications, Oxford, London, England.
- C. Polprasert, P. Kemmadamrong, F.T. Tran. (1992). Anaerobic baffle reactor (ABR) process for treating a slaughterhouse wastewater. *Environmental Technology*, 13, 857-865.
- E.H.G. Ponsano, P.M. Lacava, M.F. Pinto. (2003). Chemical composition of Rhodocyclus gelatinosus biomass produced in poultry slaughterhouse wastewater. *Brazilian Archives of Biology and Technology*, 46(2), 143-147.
- C.B.C. Raj, H.L. Quen. (2005). Advanced oxidation processes for wastewater treatment: Optimization of UV/H₂O₂ process through a statistical technique. *Chemical Engineering Science*, 60, 5305-5311.

- K.V. Rajeshwari, M. Balakrishnan, A. Kansal, K. Lata, V.V.N. Kishore. (2000).
State-of-the-art of anaerobic digestion technology for industrial wastewater treatment.
Renewable and Sustainable Energy Reviews, 4(2), 135-156.
- V. Reginatto, R.M. Teixeira, F. Pereira, W. Schmidell, A. Furigo Jr, R. Menes, C.
Etchebehere, H.M. Soares. (2005). *Brazilian Journal of Chemical Engineering*, 22(04),
593-600
- T.D. Reynolds, P. Richards. (1996). *Unit Operations and Processes in Environmental
Engineering*, 2nd Edition. PWS Publishing Company, Boston, MA.
- Reynolds number. http://en.wikipedia.org/wiki/Reynolds_number (accessed on August 20,
2009).
- M. Rodriguez, S. Malato, C. Pulgarin, S. Contreras, D. Curco, J. Gimenez, S. Esplugas.
(2005). Optimising the solar photo-Fenton process in the treatment of contaminated
water. Determination of intrinsic kinetic constants for scale-up. *Solar Energy*, 79(4),
360-368.
- J. Rodríguez-Martínez, I. Rodríguez-Garza, E. Pedraza-Flores, *et al.* (2002). Kinetics of
anaerobic treatment of slaughterhouse wastewater in batch and upflow anaerobic sludge
blanket reactor. *Bioresource Technology*, 85(3), 235-241.
- I. Ruiz, M. C. Veiga, P. Santiago, R. Blazquez. (1997). Treatment of slaughterhouse
wastewater in a UASB reactor and an anaerobic filter. *Bioresource Technology*, 60,
251-258.
- E. Salminen, J. Rintala, J. Härkönen, M. Kuitunen, H. Högmänder, A. Oikari. (2001).
Anaerobically digested solid poultry slaughterhouse wastes to be used as fertiliser on
agricultural soil. *Bioresource Technology*, 78, 81-88.
- E. Salminen, J. Rintala. (2002). Anaerobic digestion of organic solid poultry slaughterhouse
waste – a review. *Bioresource Technology*, 83, 13-26.

- M.I.A. Sanchis, J. Sáez, M. Lloréns, A. Soler, J.F. Ortuño. (2003). Particle size distribution in slaughterhouse wastewater before and after coagulation-flocculation. *Environmental Progress*, 22(3), 183-188.
- S. Sayed, W. De Zeeuw, G. Lettinga. (1984). Anaerobic treatment of slaughterhouse waste using a flocculent sludge UASB reactor. *Agricultural Wastes*, 11, 197-226.
- S. Sayed, L. Van Campen, G. Lettinga. (1987). Anaerobic treatment of slaughterhouse waste using a granular sludge UASB reactor. *Biological Wastes*, 21, 11-28.
- S. Sayed, W. De Zeeuw. (1988). The performance of a continuously operated flocculent sludge UASB reactor with slaughterhouse wastewater. *Biological Wastes*, 24, 199-212.
- K. Sehested, O.L. Rasmussen, H. Fricke. (1968). Rate constants of OH with HO_2 , O_2^- , and H_2O_2^+ from hydrogen peroxide formation in pulse-irradiated oxygenated water. The *Journal of physical chemistry*, 72, 626-631.
- T. Setiadi, Husaini, A. Djajadiningrat. (1996). Palm oil mill effluent treatment by anaerobic baffled reactors: recycle effects and biokinetic parameters. *Water Science and Technology*, 34(11), 59-66.
- H. Shemer, Y.K. Kunukcu, K.G. Linden. (2006). Degradation of the pharmaceutical Metronidazole via UV, Fenton and photo-Fenton processes. *Chemosphere*, 63, 269-276.
- J.C.H. Shih. (1993). Recent development in poultry waste digestion and feather utilization – a review. *Poultry Science*, 72, 1617-1620.
- H.Y. Shu. (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 . *Journal of Hazardous Materials*, B133, 92-98.
- D.A. Skoog, F.J. Holler, T.A. Nieman. (1998). *Principles of Instrumental Analysis*, 5th ed. (Saunders Golden Sunburst Series). Harcourt Brace College Publishers.
- D. Somayaji. (1992). Microbiological studies on biomethanation of mango peel with special

- reference to methanogens. PhD's thesis, University of Gulbarga.
- C. Sonntag, G. Mark, R. Mertens, M.N. Schuchmann, H.P. Schuchmann. (1993). UV radiation and/or oxidants in water pollution control. *Journal of Water Supply: Research and Technology-Aqua*, 42(4), 201-211.
- J. Staehelin, R. E. Buehler, J. Hoigne. (1984). Ozone decomposition in water studied by pulse radiolysis. 2. Hydroxyl and hydrogen tetroxide (HO₄) as chain intermediates. *The Journal of physical chemistry*, 88, 5999-6004.
- M.I. Stefan, A.R. Hoy, J.R. Bolton. (1996). Kinetics and mechanism of the degradation and mineralization of acetone in dilute aqueous solution sensitized by the UV photolysis of hydrogen peroxide. *Environmental Science and Technology*, 30, 2382-2390.
- T. Stephenson, J.N. Lester. (1985). Evaluation of startup and operation of four anaerobic processes treating a synthetic meat waste. *Biotechnology and Bioengineering*, 28, 372-380.
- The World Bank. (1998). Pollution Prevention and Abatement Handbook.
http://www-wds.worldbank.org/external/default/WDSCContentServer/WDSP/IB/1999/06/03/000094946_99040905052283/Rendered/PDF/multi0page.pdf (accessed on October 12, 2007).
- G.B. Tabrizi, M. Mehrvar. (2004). Integration of advanced oxidation technologies and biological processes: recent developments, trends, and advances. *Journal of Environmental Science & Health, Part A: Toxic/Hazardous Substances & Environmental Engineering*, 39(11/12), 3029-3081.
- G.B. Tabrizi, M. Mehrvar. (2006). Pilot-plant study for the photochemical treatment of aqueous linear alkylbenzene sulfonate. *Separation & Purification Technology*, 49(2), 115-121.
- F. Toldrá, A. Flors, J.L. Lequerica, S. Vallès. (1987). Fluidized bed anaerobic biodegradation

- of food industry wastewaters. *Biological Wastes*, 21(1), 55-61.
- R. Toor, M. Mohseni. (2007). UV-H₂O₂ based AOP and its integration with biological activated carbon treatment for DBP reduction in drinking water. *Chemosphere*, 66(11), 2087-2095.
- A. Torkian, A. Egbali, S.J. Hashemian. (2003). The effect of organic loading rate on the performance of UASB reactor treating slaughterhouse effluent. *Resources, Conservation and Recycling*, 40, 1-11.
- W.P. Tritt, F. Schuchardt. (1992). Materials flow and possibilities of treating liquid and solid wastes from slaughterhouses in Germany. *Bioresource Technology*, 41, 235-245.
- W.P. Tritt. (1992). The anaerobic treatment of slaughterhouse wastewater in fixed-bed reactors. *Bioresource Technology*, 41, 201-207.
- UNEP/MAP (United Nations Environment Programme/Mediterranean Action Plan). (2004). Guidelines for the application of best available techniques (BATs) and best environmental practices (BEPs) in industrial sources of BOD, Nutrients and suspended solids for the Mediterranean Region. Athens.
- http://www.cprac.org/pdf/estudis/generals/guiaBATsfonsindustrials_eng.pdf (accessed on October 15, 2007).
- US EPA. (2002). Development document for the proposed effluent limitations guidelines and standards for the meat and poultry products industry point source category (40 CFR 432).
- S. Uyanik, P.J. Sallis, G.K. Anderson. (2002). The treatment of polymer addition on granulation in an anaerobic baffled reactor (ABR). Part I: process performance. *Water Research*, 36, 933-943.
- S. Uyanik. (2003). A novel anaerobic reactor: Split fed anaerobic baffled reactor (SFABR). *Turkish Journal of Engineering Environment and Science*, 27. 339-345.
- B. Varatharajan, A. Kanmani. (2007). Treatability study of pharmaceutical wastewater by

- combined solar photo fenton and activated sludge process. *Journal of Industrial Pollution Control*, 23, 157-164.
- M.T. Velásquez, J. Martínez, I. Monje-Ramírez, M.N. Rojas-Valencia. (2004). Destruction of helminth (*Ascaris suum*) eggs by ozone. *Science and Engineering*, 26, 359-366.
- L.A.H.M. Verheijen, D. Wiersema, P. Hulshoff, J. de Wit. (1996). Management of waste from animal product processing. FAO/WB Consultancy Report for Livestock and Environment Study. International Agricultural Centre, Wageningen, The Netherlands.
- S.H. Venhuis, M. Mehrvar. (2005). Photolytic treatment of aqueous linear alkylbenzene sulfonate. *Journal of Environmental Science & Health, Part A: Toxic/Hazardous Substances & Environmental Engineering*, 40(9), 1731-1739.
- T. Viraraghavan, S. R. Kikkeri. (1988). Peat filtration of food-processing wastewater. *Biological Wastes*, 26, 151-155.
- M. Vossoughi, M. Shakeri, I. Alemzadeh. (2003). Performance of anaerobic baffled reactor treating synthetic wastewater influenced by decreasing COD/SO₄ ratios. *Chemical Engineering and Processing*, 42, 811-816.
- J.S. White, S.E. Bayley, P.J. Curtis. (2000). Sediment storage of phosphorus in a northern prairie wetland receiving municipal and agro-industrial wastewater. *Ecological Engineering*, 14, 127-138.
- J. Wu, H. Doan. (2005). Disinfection of recycled red-meat-processing wastewater by ozone. *Journal of Chemical Technology & Biotechnology*, 80(7), 828-833.
- H. Zhou, D.W. Smith. (2002). Advanced technologies in water and wastewater treatment. *J. Environmental Engineering and Science*, 1, 247-264.
- P. Zhou, C. Su, B. Li, Y. Qian. (2006). Treatment of high-strength pharmaceutical wastewater and removal of antibiotics in anaerobic and aerobic biological treatment processes. *Journal of Environmental Engineering*, 132(1), 129-136.

APPENDICES

Appendix A. Determination of TOC and TN of Synthetic Wastewater

As mentioned in Section (3.1), the carbon source of the synthetic slaughterhouse wastewater came from the meat extract (17 amino acids) and glycerol, whilst the nitrogen source came from the similar meat extract and ammonium chloride. The calculated values of total organic carbon (TOC) and total nitrogen (TN) of the initial synthetic wastewater based on these 17 amino acids are shown in Table A.1.

Taking alanine (AL , $C_3H_7NO_2$) as calculation sample, the % w of TOC /w of meat extract and the % w of TN /w of meat extract in the initial wastewater are determined as follows:

$$TOC_{AL} (\%w/w) = \frac{\text{Carbon Molar Mass}}{AL \text{ Molar Mass}} \times \%w_{AL} / w_{Meat \text{ Extract}} = \frac{36.03mgC}{89.1mgAL} \times \frac{5.85mgAL}{100mgMeat \text{ Extract}}$$

$$= \frac{2.37mgC}{100mgMeat \text{ Extract}}$$

$$TN_{AL} (\%w/w) = \frac{\text{Nitrogen Molar Mass}}{AL \text{ Molar Mass}} \times \%w_{AL} / w_{Meat \text{ Extract}} = \frac{14.0mgN}{89.1mgAL} \times \frac{5.85mgAL}{100mgMeat \text{ Extract}}$$

$$= \frac{0.92mgN}{100mgMeat \text{ Extract}}$$

1,950 mg/L of the meat extract, 200 mg/L of glycerol ($C_3H_8O_3$), and 360 mg/L of ammonium chloride (NH_4Cl) were used in the synthetic wastewater. Therefore, the total concentrations of TOC and TN are estimated as follows:

$$TOC(mgC/L) = \frac{1950mgMeat \text{ Extract}}{L} \times \frac{31.5mgC}{100mgMeat \text{ Extract}} + \frac{200mgC_3H_8O_3}{L} \times \frac{36.0mgC}{92.1mgC_3H_8O_3}$$

$$= 692mgC/L$$

$$TN(mgN/L) = \frac{1950mgMeat \text{ Extract}}{L} \times \frac{13.3mgN}{100mgMeat \text{ Extract}} + \frac{360mgNH_4Cl}{L} \times \frac{14.0mgN}{53.5mgNH_4Cl}$$

$$= 354mgN/L$$

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

Chemical Symbol	Typical Amino Acids	% w of chemical/w of meat extract	Molar Mass (g/mol)	Carbon Molar Mass (g/mol)	Nitrogen Molar Mass (g/mol)	% w of TOC/w of meat extract	% w of TN/w of meat extract
AL	ALANINE (C ₃ H ₇ NO ₂)	5.85	89.1	36.03	14.0	2.37	0.92
AR	ARGININE (C ₆ H ₁₄ N ₄ O ₂)	7.10	174.2	72.06	56.0	2.94	2.28
AS	ASPARTIC ACID (C ₄ H ₇ NO ₄)	5.10	133.1	48.04	14.0	1.84	0.54
CY	CYSTEINE (C ₃ H ₇ NO ₂ S)	0.68	121.2	36.03	14.0	0.20	0.08
G.A	GLUTAMIC ACID (C ₅ H ₉ NO ₄)	10.71	147.1	60.05	14.0	4.37	1.02
GL	GLYCINE (C ₂ H ₅ NO ₂)	10.85	75.1	24.02	14.0	3.47	2.02
IS	ISOLEUCINE (C ₆ H ₁₃ NO ₂)	3.17	131.2	72.06	14.0	1.74	0.34
LE	LEUCINE (C ₆ H ₁₃ NO ₂)	3.15	131.2	72.06	14.0	1.73	0.34
LY	LYSINE (C ₆ H ₁₄ N ₂ O ₂)	4.78	146.2	72.06	28.0	2.36	0.92
ME	METHIONINE (C ₅ H ₁₁ NO ₂ S)	2.61	149.2	60.05	14.0	1.05	0.24
PH	PHENYLALANINE (C ₉ H ₉ NO ₂)	2.34	165.2	108.09	14.0	1.53	0.20
PR	PROLINE (C ₅ H ₉ NO ₂)	7.79	115.1	60.05	14.0	4.06	0.95
SE	SERINE (C ₃ H ₇ NO ₃)	1.87	105.1	36.03	14.0	0.64	0.25
TH	THREONINE (C ₄ H ₉ NO ₃)	2.54	119.1	48.04	14.0	1.02	0.30
TR	TRYPTOPHAN (C ₁₁ H ₁₂ N ₂ O ₂)	0.34	204.2	132.11	28.0	0.22	0.05
TY	TYROSINE (C ₉ H ₉ NO ₃)	0.66	181.2	108.09	14.0	0.39	0.05
VA	VALINE (C ₅ H ₁₁ NO ₂)	3.06	117.2	60.05	14.0	1.57	0.37
Total						31.5	10.9

Appendix B. Determination of Standard Deviation and Relative Error

Relative error is used to express an accuracy of an accept value of the quantity being measured, which is determined as follows (Skoog *et al*, 1998). Relative error could be positive, zero, or negative indicating that the measured value is smaller than, equal to or greater than the mean of a set of data. The lowest average absolute relative error was used as criterion to select a kinetic model for the ABR and the UV/H₂O₂ processes.

$$\text{Relative error} = \frac{\bar{x} - x_i}{x_i} \times 100\% \quad (\text{B.1})$$

where x_i is an accepted value; and $\bar{x}$ is mean of a finite set of data.

Sample standard deviation is used to analyze the accuracy of an experimental measurement for a finite set of experimental data. Sample mean ($\bar{x}$) and sample standard deviation (s) are determined as follows (Skoog *et al.*, 1998).

$$\bar{x} = \frac{\sum_{i=1}^N x_i}{N} \quad (\text{B.2})$$

$$s = \sqrt{\frac{\sum_{i=1}^N (x_i - \bar{x})^2}{N - 1}} \quad (\text{B.3})$$

where x_i is the measurement value of sample i ; and N is the total number of measurements.

For example, the influent CBOD₅ concentrations of two samples were determined to be in 1020 and 1032 mg/L, respectively, at the HRT 0.9 days in the ABR process. Therefore, the mean, the sample standard deviation, the relative error, and the average relative error of the influent CBOD₅ concentrations are determined as follows.

$$\bar{x} = \frac{1020.0 + 1032.0}{2} = 1026.0 \text{ mg/L}$$

$$s = \sqrt{\frac{(1020.0 - 1026.0)^2 + (1032.0 - 1026.0)^2}{2 - 1}} = 8.5 \text{ mg/L}$$

$$\text{Relative error 1} = \frac{1026.0 - 1020.0}{1020.0} \times 100\% = 0.6\%$$

$$\text{Relative error 2} = \frac{1026.0 - 1032.0}{1032.0} \times 100\% = -0.6\%$$

$$\text{Average relative error} = \frac{0.6\% - 0.6\%}{2} = 0$$

$$\text{Average absolute relative errors} = \frac{0.6\% + 0.6\%}{2} = 0.6\%$$

Appendix C. Determination of TSS and VSS

The TSS and VSS were determined by Equations (3.3) and (3.4) based on *Standard Methods* (APHA *et al.*, 1998).

$$TSS(\text{mg/L}) = \frac{(W_1 - W_2 - W_3)}{V} \quad (3.3)$$

$$VSS(\text{mg/L}) = \frac{(W_1 - W_2 - W_3) - (W_4 - W_5)}{V} = TSS - \frac{W_4 - W_5}{V} \quad (3.4)$$

where all parameters are the same as defined in Section 3.4.3.

For example, at a HRT of 0.9 days (27.6 mL/min of flowrate) of the ABR, the TSS and VSS of sludge in the compartment 1 are shown in Table C.1.

Table C.1: Calculation for TSS and VSS of sludge in compartment 1 of ABR process

Sample Testing	Compartment 1
(1) Volume of sludge (mL)	5.0
(2) Weight of filter (g)	0.9
(3) Weight of Al weighting dish (g)	1.3
(4) Total weight of filter and Al dish after 1 h heating in the oven at 104°C (g)	2.3
(5) Total weight of filter and Al dish after 15 min igniting in the furnace at 550 °C (g)	1.3
(6) TSS = (4)-(3)-(2) (g)	0.1
(7) VSS = (4)-(5)-(2) (g)	0.1
(8) Concentration of TSS in sludge =(6)/(1)×1000 (g/L)	11.6
(9) Concentration of VSS in sludge =(7)/(1)×1000 (g/L)	9.2

Appendix D. Determination of CBOD₅

CBOD₅ of wastewater was determined by the following equation based on 5210B Standard Methods (APHA *et al.*, 1998).

$$CBOD_5 = \frac{(D_1 - D_2) - SCF}{P} \quad (C.1)$$

$$SCF = (B_1 - B_2)f \quad (C.2)$$

where:

- D_1 is the DO of a diluted sample immediately after preparation, mg/L;
- D_2 is the DO of the same diluted sample after 5 days incubation at 20°C, mg/L;
- SCF is seed correction factor, mg/L;
- P is decimal volumetric fraction of sample used, where $P = \text{volume of sample} / \text{volume of BOD-bottle}$;

- B_1 is the DO of seed control before incubation, mg/L ;
- B_2 is the DO of seed control after incubation, mg/L ; and
- f is the ratio of the volume of polyseed solution in glucose-glutamic acid (GGA) test to the volume of polyseed solution in seed control.

For example, the influent CBOD₅ concentration was measured at the HRT of 0.9 days in the ABR process. Each 300- mL BOD bottle contained 1 mL of influent wastewater ($P=1/300$). The volume of polyseed solution used in GGA test was 4 mL . Three seed controls were prepared using 10, 15, 20 mL of polyseed solution, respectively. A DO meter (YSI 58 Dissolved Oxygen Meter, YSI Inc.) and a BOD bottle probe (YSI 5750 Non-Stirring BOD Bottle Probe, YSI Inc.) were used to measure the DO of all samples. The DO of the dilution water (D_1) was measured to be 9.5 mg/L . The average D_2 of two diluted influent wastewater samples was 5.5 mg/L . The D_2 of the 3 seed controls measured by the DO meter and SCF values are showed in Table D.1.

Therefore, the influent CBOD₅ of the wastewater at the HRT of 0.9 days in the ABR process was determined as follows.

$$CBOD_5 = \frac{(9.5 - 5.5) - 0.6}{1/300} = 1026.0 \text{ } mg/L$$

Table D.1: Calculation for SCF

Sample ID	Initial DO: B_1 (mg/L)	DO after 5 days: B_2 (mg/L)	f	SCF (mg/L)	Average of SCF (choose the value > 0.6-1.0 mg/L)*
Seed control 1	9.5	7.9	4/10 = 0.4	0.6	= (0.6+0.6)/2 = 0.6
Seed control 2	9.5	7.6	4/15 = 0.3	0.5	
Seed control 3	9.5	6.4	4/20 = 0.2	0.6	

* BOD₅ Training Videos provided by InterLab® Supply (<http://polyseed.com/videos/index.php>)

Appendix E: Reynolds number in the ABR, the UV/H₂O₂, and the combined processes

For flow in a pipe or tube and in a rectangular duct, the Reynolds number is determined by Equation (3.8).

$$Re = \frac{\rho u L}{\mu} = \frac{\rho Q L}{\mu a} \quad (3.8)$$

Where:

- Re is Reynolds number (dimensionless);
- u is the mean fluid velocity, m/s ;
- L is a characteristic length that the flow is going through or around, m ; for a pipe or a tube, L equals to the diameter of the pipe or tube; for a rectangular duct, L equals to the hydraulic diameter of the rectangular duct, which is 4 times the cross-sectional area divided by the wetted perimeter, P ;
- μ is the dynamic viscosity of the fluid, $kg/m.s$, for water at 25°C, $\mu=8.98 \times 10^{-4} kg/m.s$;
- ρ is the density of the fluid, kg/m^3 , for water at 25°C, $\rho=1000 kg/m^3$;
- Q is the volumetric flow rate, m^3/s ; and
- a is cross-sectional area, m^2 .

For example, the length and width of the ABR reactor are 10 and 15 cm , respectively. At the flowrate of 27.6 mL/min , the hydraulic diameter of the ABR and the Reynolds number are determined as follows. The calculation results of the Reynolds number in the ABR, the UV/H₂O₂ and their combined processes are shown in Table E.1.

$$L = \frac{4 \times a}{P} = \frac{4 \times 10cm \times \frac{1m}{100cm} \times 15cm \times \frac{1m}{100cm}}{2 \times (10cm + 15cm) \times \frac{1m}{100cm}} = 0.12m$$

$$Re = \frac{\rho Q L}{\mu a} = \frac{1000 \frac{kg}{m^3} \times 27.6 \frac{mL}{min} \times \frac{1m^3}{10^6 mL} \times \frac{1min}{60s} \times 0.12m}{8.98 \times 10^{-4} \frac{kg}{m.s} \times 10cm \times \frac{1m}{100cm} \times 15cm \times \frac{1m}{100cm}} = 4.1$$

Table E.1: Reynolds number in the ABR, the UV/H₂O₂ and their combined processes

Process	Flowrate (mL/min)	Flowrate (m ³ /s)	Length×width or Diameter (cm)	Length×width or Diameter (m)	Characteristic length (m)	Cross-sectional area (m ²)	Re
ABR	27.6	4.6×10 ⁻⁷	10×15	0.10×0.15	0.12	0.015	4.1
	13.5	2.3×10 ⁻⁷					2.0
	10.5	1.8×10 ⁻⁷					1.6
	8.8	1.5×10 ⁻⁷					1.3
	6.2	1.0×10 ⁻⁷					0.9
UV alone	45.0	7.5×10 ⁻⁷	5.5	5.5	5.5	0.0024	19.3
	22.5	3.8×10 ⁻⁷					9.7
	15.0	2.5×10 ⁻⁷					6.5
	11.25	1.9×10 ⁻⁷					4.8
	9.0	1.5×10 ⁻⁷					3.9
UV in combined processes	27.6	4.6×10 ⁻⁷	5.5	5.5	5.5	0.0024	11.9
	13.5	2.3×10 ⁻⁷					5.8
	10.5	1.8×10 ⁻⁷					4.5
	8.8	1.5×10 ⁻⁷					3.8
	6.2	1.0×10 ⁻⁷					2.7

Appendix F. TOC, TN, COD, and CBOD₅ Profiles of the Wastewater

Table F.1: TOC, TN, COD, and CBOD₅ Profiles in the ABR Process in the ABR Process

Flowrate (mL/min)	HRT (days)	Parameter (mg/L)	Inlet	Compartment				
				1	2	3	4	5
27.6	0.9	TOC	948.3	582.4	541.8	507.8	463.9	385.4
		TOC removal (%)	0.0	38.6	42.9	46.5	51.1	59.4
		Sample S. D.	30.8	33.6	54.4	7.1	41.2	2.3
		TN	328.5	327.1	334.1	349.2	357.3	339.9
		TN change (%)	0.0	0.4	(1.7)	(6.3)	(8.8)	(3.5)
		Sample S. D.	30.4	16.7	29.4	11.0	21.1	0.2
		COD	2128.3	1164.5	985.6	887.2	804.2	769.3
		COD removal (%)	0.0	45.3	53.7	58.3	62.2	63.9
		CBOD ₅	1026.0	547.0	377.0	287.0	197.0	157.0
		CBOD ₅ removal (%)	0.0	46.7	63.3	72.0	80.8	84.7
		Sample S. D.	8.5	11.3	9.9	5.7	5.7	7.1
		CBOD ₅ /COD	0.5	0.5	0.4	0.3	0.2	0.2
		CBOD ₅ /TOC	1.1	0.9	0.7	0.6	0.4	0.4
		COD/TOC	2.2	2.0	1.8	1.7	1.7	2.0
13.5	1.7	TOC	671.0	248.8	145.4	117.4	114.9	110.9
		TOC removal (%)	0.0	62.9	78.3	82.5	82.9	83.5
		Sample S. D.	4.0	7.9	4.3	8.3	9.7	6.8
		TN	338.9	339.3	360.7	355.2	367.3	358.6
		TN change (%)	0.0	(0.1)	(6.4)	(4.8)	(8.4)	(5.8)
		Sample S. D.	1.5	15.0	2.1	7.3	0.5	3.6
		CBOD ₅	631.2	331.2	187.2	103.2	103.2	91.2
		CBOD ₅ removal (%)	0.0	47.5	70.3	83.7	83.7	85.6
		Sample S. D.	23.8	10.2	13.6	5.4	3.4	6.8
		CBOD ₅ /TOC	0.9	1.3	1.3	0.9	0.9	0.8
10.5	2.2	TOC	968.6	165.7	133.3	110.9	116.4	117.4
		TOC removal (%)	0.0	82.9	86.2	88.5	88.0	87.9
		Sample S. D.	60.7	2.8	11.7	7.1	7.7	7.2
		TN	380.3	367.9	348.7	373.5	379.5	385.7
		TN change (%)	0.0	3.3	8.3	1.8	0.2	(1.4)
		Sample S. D.	26.6	4.3	17.7	0.7	0.3	2.1
		CBOD ₅	924.0	249.0	159.0	129.0	99.0	99.0
		CBOD ₅ removal (%)	0.0	73.1	82.8	86.0	89.3	89.3
		Sample S. D.	42.4	29.7	17.0	21.2	8.5	8.5
		CBOD ₅ /TOC	1.0	1.5	1.2	1.2	0.9	0.8

Table F.1: TOC, TN, COD, and CBOD₅ Profiles in the ABR Process in the ABR Process

(Continued)

Flowrate (mL/min)	HRT (days)	Parameter (mg/L)	Inlet	Compartment				
				1	2	3	4	5
8.8	2.7	TOC	564.6	123.2	74.0	67.0	60.0	64.4
		TOC removal (%)	0.0	78.2	86.9	88.1	89.4	88.6
		Sample S. D.	23.8	6.5	4.0	3.6	0.7	1.1
		TN	379.7	374.2	377.3	378.0	385.8	393.0
		TN change (%)	0.0	1.4	0.6	0.5	(1.6)	(3.5)
		Sample S. D.	5.7	5.2	1.8	9.3	4.7	0.7
		CBOD ₅	570.0	300.0	210.0	150.0	90.0	60.0
		CBOD ₅ removal (%)	0.0	47.4	63.2	73.7	84.2	89.5
		Sample S. D.	33.9	25.5	0.0	12.7	12.7	4.2
6.2	3.8	CBOD ₅ /TOC	1.0	2.4	2.8	2.2	1.5	0.9
		TOC	973.3	131.5	118.5	110.7	105.6	98.4
		TOC removal (%)	0.0	86.5	87.8	88.6	89.1	89.9
		Sample S. D.	40.0	19.7	17.8	18.0	13.1	19.0
		TN	343.6	332.9	339.9	339.0	341.4	337.4
		TN change (%)	0.0	3.1	1.1	1.3	0.6	1.8
		Sample S. D.	5.7	1.7	2.5	1.3	2.2	1.9
		COD	2302.5	232.6	196.4	79.4	76.3	53.9
		COD removal (%)	0.0	89.9	91.5	96.6	96.7	97.7
		CBOD ₅	940.5	145.8	43.8	37.8	37.8	31.8
		CBOD ₅ removal (%)	0.0	84.5	95.3	96.0	96.0	96.6
		Sample S. D.	63.6	1.7	3.4	2.5	2.5	6.8
		CBOD ₅ /COD	0.4	0.6	0.2	0.5	0.5	0.6
		CBOD ₅ /TOC	1.0	1.1	0.4	0.3	0.4	0.3
		COD/TOC	2.4	1.8	1.7	0.7	0.7	0.5

Note: 1. Sample S.D.: Sample Standard Deviation, 2. number in parentheses is negative, 3. DO range: 0.5-1.6 mg/L.

Table F.2: TOC, TN, COD, and CBOD₅ Profiles in the UV/H₂O₂ Process

H ₂ O ₂ dosage (mg/L)	Inlet Condition	Parameter (mg/L)	HRT (h)						
			Inlet	Dark	0.5	1.0	1.5	2.0	2.5
529	Untreated	TOC	968.4	958.0	942.2	936.4	934.4	911.1	907.7
		TOC removal (%)	0.0	1.1	2.7	3.3	3.5	5.9	6.3
		Sample S. D.	53.8	50.6	37.6	50.2	46.2	28.2	46.6
		TN	442.4	431.8	437.5	435.5	432.1	441.5	427.3
		TN change (%)	0.0	2.4	1.1	1.6	2.3	0.2	3.4
		Sample S. D.	23.3	26.8	15.4	30.4	27.8	25.0	33.7
529	Untreated	TOC	492.2	484.1	487.4	467.8	460.0	459.3	450.7
		TOC removal (%)	0.0	1.6	1.0	5.0	6.5	6.7	8.4
		Sample S. D.	42.4	38.7	13.4	34.1	22.0	8.7	9.8
		TN	188.7	181.1	189.9	189.4	180.0	197.8	196.4
		TN change (%)	0.0	4.0	(0.6)	(0.4)	4.6	(4.8)	(4.1)
		Sample S. D.	20.0	20.3	12.9	13.3	16.5	4.7	4.0
1371	Untreated	TOC	492.7	490.0	451.3	441.9	428.8	406.6	378.6
		TOC removal (%)	0.0	0.5	8.4	10.3	13.0	17.5	23.2
		Sample S. D.	35.4	33.2	11.0	41.9	12.9	19.6	9.1
		CBOD ₅	660.0	–	585.0	585.0	540.0	495.0	345.0
		CBOD ₅ removal (%)	0.0	–	11.4	11.4	18.2	25.0	47.7
		Sample S. D.	63.6	–	31.8	31.8	19.1	29.7	10.6
		CBOD ₅ /TOC	1.3	–	1.3	1.3	1.3	1.2	0.9
		TN	186.0	185.0	178.8	180.0	175.7	194.6	191.8
		TN change (%)	0.0	0.6	3.9	3.2	5.6	(4.6)	(3.1)
529	Untreated	Sample S. D.	14.4	11.3	9.4	24.2	8.2	7.7	5.0
		TOC	156.0	148.4	143.8	130.4	119.3	111.0	102.2
		TOC removal (%)	0.0	4.9	7.9	16.4	23.5	28.8	34.5
		Sample S. D.	13.7	4.1	16.8	4.5	5.0	8.3	8.5
		COD	357.5	–	306.2	245.7	200.0	144.1	58.4
		COD removal (%)	0.0	–	14.3	31.3	44.0	59.7	83.7
		CBOD ₅	149.5	–	84.5	74.5	74.5	69.5	34.5
		CBOD ₅ removal (%)	0.0	–	43.5	50.2	50.2	53.5	76.9
		Sample S. D.	7.8	–	3.5	2.8	2.8	5.7	4.9
		CBOD ₅ /COD	0.4	–	0.3	0.3	0.4	0.5	0.6
		COD/TOC	2.3	–	2.1	1.9	1.7	1.3	0.6
		TN	68.7	67.3	69.6	65.5	67.7	67.7	67.0
		TN change (%)	0.0	2.1	(1.4)	4.6	1.4	1.4	2.4
		Sample S. D.	4.8	1.8	8.7	3.6	3.8	3.3	4.1

Table F.2: TOC, TN, COD, and CBOD₅ Profiles in the UV/H₂O₂ Process (Continued)

H ₂ O ₂ dosage (mg/L)	Inlet Condition	Parameter (mg/L)	HRT (h)						
			Inlet	Dark	0.5	1.0	1.5	2.0	2.5
1371	Untreated	TOC	157.6	153.1	123.7	118.9	90.6	83.8	56.3
		TOC removal (%)	0.0	2.8	21.5	24.5	42.5	46.8	64.3
		Sample S. D.	9.4	7.1	5.4	3.3	7.9	5.6	0.1
		COD	-	-	-	-	313.7	203.8	100.3
		CBOD ₅	124.5	-	74.5	49.5	34.5	28.5	19.5
		CBOD ₅ removal (%)	0.0	-	40.2	60.2	72.3	77.1	84.3
		Sample S. D.	14.1	-	7.1	2.1	1.4	2.1	3.5
		CBOD ₅ /COD	-	-	-	-	0.1	0.1	0.2
		COD/TOC	-	-	-	-	3.5	2.4	1.8
		TN	68.1	68.8	68.9	68.4	67.9	70.7	65.9
		TN change (%)	0.0	(1.1)	(1.2)	(0.5)	0.2	(3.9)	3.1
		Sample S. D.	5.2	3.7	3.8	4.2	4.4	4.2	2.5
529	ABR treated	TOC	157.3	149.1	133.2	120.5	107.0	102.7	100.4
		TOC removal (%)	0.0	5.2	15.4	23.4	32.0	34.7	36.2
		Sample S. D.	8.5	4.6	11.7	7.9	9.4	8.9	8.3
		TN	372.5	367.1	375.2	384.3	359.1	400.5	396.5
		TN change (%)	0.0	1.5	(0.7)	(3.2)	3.6	(7.5)	(6.4)
		Sample S. D.	20.9	3.6	20.6	7.7	19.2	19.5	45.7
1371	ABR treated	TOC	155.0	150.3	134.2	107.8	102.7	99.3	97.3
		TOC removal (%)	0.0	3.0	13.4	30.5	33.7	35.9	37.3
		Sample S. D.	8.4	7.3	4.5	7.6	10.2	2.7	10.1
		COD	286.8	-	138.7	98.0	93.7	92.6	86.9
		COD removal (%)	0.0	-	51.6	65.8	67.3	67.7	69.7
		CBOD ₅	96.0	-	70.0	60.0	60.0	50.0	45.0
		CBOD ₅ removal (%)	0.0	-	27.1	37.5	37.5	47.9	53.1
		Sample S. D.	5.1	-	4.9	5.9	5.9	4.2	2.1
		CBOD ₅ /COD	0.3	-	0.5	0.6	0.6	0.5	0.5
		COD/TOC	1.8	-	1.0	0.9	0.9	0.9	0.9
		TN	378.9	374.9	387.0	378.7	387.1	393.0	380.3
		TN change (%)	0.0	1.1	(2.1)	0.1	(2.2)	(3.7)	(0.4)
		Sample S. D.	27.3	37.8	16.6	20.6	33.0	4.8	31.7

Note: Note: 1. Sample S.D.: Sample Standard Deviation, 2. number in parentheses is negative.

Table F.3: TOC and TN Profiles at HRT of 49, 100, 129, 153, 218 *min* in the UV/H₂O₂ of the
Combined Processes

Flowrate (mL/min)	H ₂ O ₂ (mL)	H ₂ O ₂ Dose (mg/L)	TOC (mg/L)	TOC removal (%)		Sample S. D. (mg/L)	TN (mg/L)	TN change in UV (%)	Sample S. D. (mg/L)
				UV ^a	Overall ^b				
27.6	-	ABR inlet ^c	948.3	-	-	30.8	328.5	-	30.4
	-	C5 outlet ^d	385.4	0	59.4	2.3	339.9	0.0	0.2
	0	0	380.6	1.3	59.9	25.2	336.3	1.1	4.3
	10	294	360.7	6.4	62	17.6	363.2	(6.9)	9.5
	15	440	379	1.7	60	15	341.6	(0.5)	8.2
	18	529	322	16.5	66	3.1	333.7	1.8	0.3
	20	587	362.6	5.9	61.8	33.8	325.3	4.3	17
	25	734	408.1	-	57	24.9	344.7	(1.4)	4.3
13.5	-	ABR inlet ^c	671	-	-	4	338.9	-	1.5
	-	C5 outlet ^d	110.9	0	83.5	6.8	358.6	0.0	3.6
	0	0	108.9	1.8	83.8	1.6	357.6	0.3	2
	3	258	110.4	0.5	83.5	9.3	347.2	3.2	5.5
	5	430	97.3	12.3	85.5	12.9	331.8	7.5	13.2
	7	602	81.7	26.4	87.8	4.1	329.9	8.0	1.1
	10	859	90.4	18.5	86.5	11.5	340.4	5.1	5.5
	15	1289	105.4	5	84.3	2.3	311.2	13.2	3.5
10.5	-	ABR inlet ^c	968.6	-	-	60.7	380.3	-	26.6
	-	C5 outlet ^d	117.4	0	87.9	7.2	385.7	0.0	2.1
	0	0	91.4	22.1	90.6	7.8	352.7	8.6	7.1
	3	180	82.4	29.8	91.5	5.8	338.9	12.1	1.3
	6	360	78.9	32.8	91.9	3.6	353.8	8.3	1.2
	9	540	68.9	41.3	92.9	0.9	338.5	12.2	4.8
	12	720	63.4	46	93.5	4.8	341.5	11.5	14.9
	15	900	101.2	13.8	89.6	3.8	365.8	5.2	1.5

Table F.3: TOC and TN Profiles at HRT of 49, 100, 129, 153, 218 min in the UV/H₂O₂ of the

Combined Processes (Continued)

Flowrate (ml/min)	H ₂ O ₂ (mL)	H ₂ O ₂ Dose (mg/L)	TOC (mg/L)	TOC removal (%)		Sample S. D. (mg/L)	TN (mg/L)	TN change in UV (%)	Sample S. D. (mg/L)
				UV ^a	Overall ^b				
8.8	-	ABR inlet ^c	564.6	-	-	23.8	379.7	-	5.7
	-	C5 outlet ^d	64.4			1.1	393		0.7
	-		(32.2 ^e)	0	88.6		(196.5 ^f)	0.0	
	0	0	35.4	-	93.7	2.8	249.1	(26.8)	1.9
	0.5	56	30.6	4.8	94.6	1	265.3	(35.0)	20.2
	1.5	168	17	47.1	97.9	1.3	228.2	(16.1)	13.9
	3	344	8.7	73.1	98.5	0.9	252.5	(28.5)	1.5
	5	561	6.8	78.7	98.8	0.8	179.7	8.5	10.1
	10	1122	3.5	89	99.4	0.2	140.1	28.7	3.5
	15	1737	16.3	49.4	97.1	1.5	142.1	27.7	15.9
6.2	-	ABR inlet ^c	973.3	-	-	40	343.6		5.7
	-	C5 outlet ^d	98.4	0	89.9	18.9	337.4	0.0	1.9
	0	0	-	-	-	-	-	-	-
	3.8	367	92.4	6.2	90.5	2.1	243.6	27.8	4.9
	6	588	76.3	22.5	92.2	13.1	265.5	21.3	21.1
	9	881	76.1	22.7	92.2	10.8	270.5	19.8	11.2
	12	1175	66.8	32.2	93.1	9.5	311	7.8	2
	14	1371	48.5	50.8	95	12.1	266.2	21.1	11.1
	15	1469	58.5	40.5	94	19.1	317.5	5.9	1.7
	18	1763	63.8	35.2	93.4	6.3	323.5	4.1	2.1
	21	2057	73.5	25.3	92.4	17.5	321.8	4.6	11.1

Notes: 1. Sample S.D.: Sample Standard Deviation, 2. number in parentheses is negative.

^a TOC removal in the UV photoreactor;

^b Overall TOC removal in the combined processes;

^c Influent concentration of the ABR, and the values were used as the influent concentration to calculate the overall TOC removal in the combined processes;

^d Effluent concentration of the compartment 5, and the values were used as the influent concentrations to calculate the TOC removal in the UV photoreactor;

^{e, f} Half values of C5 outlet because C5 outlet was diluted by H₂O₂ solution, and ^e was used as influent concentration to calculate the TOC removal in the UV photoreactor.

Appendix G: TOC, COD, and CBOD5 Removal of the Wastewater

Figure G.1: TOC removal in each ABR compartment at the HRT of 0.9, 1.7, 2.2, 2.7 and 3.8 days, respectively.

Figure G.2: COD removal in each ABR compartment at the HRT of 0.9, 1.7, 2.2, 2.7 and 3.8 days, respectively.

Figure G.3: CBOD₅ removal in each ABR compartment at the HRT of 0.9, 1.7, 2.2, 2.7 and 3.8 days, respectively.

Figure G4: TOC removal of the untreated wastewater at various HRT and various H_2O_2 dosages in the UV/ H_2O_2 process alone.

Figure G.5: COD removal of the untreated wastewater at various HRT and the H_2O_2 dosages of $1371 \text{ mgH}_2\text{O}_2/\text{L}$ in the UV/ H_2O_2 process alone.

Figure G6: CBOD₅ removal of the untreated wastewater at various HRT and various H₂O₂ dosages in the UV/H₂O₂ process alone.

Figure G.7: TOC removal in the combined processes with the HRT of 0.9, 1.7, 2.2, 2.7, and 3.8 days in the ABR and 49, 100, 129, 153 and 218 min in the UV/H₂O₂.

Figure G.8: TOC removal of the ABR treated or untreated wastewater at the H_2O_2 dosages of 529 and 1371 $\text{mgH}_2\text{O}_2/\text{L}$ and various HRT in the UV/ H_2O_2 process.

Figure G.9: COD removal of the ABR treated and untreated wastewater with 0.013 M of TOC concentration at the H_2O_2 dosages of 1371 $\text{mgH}_2\text{O}_2/\text{L}$ and various HRT in the UV/ H_2O_2 process.

Figure G.10: CBOD₅ removal of the ABR treated and untreated wastewater with 0.013 *M* of TOC concentration at the H₂O₂ dosages of 1371 mgH₂O₂/L and various HRT in the UV/H₂O₂ process.

Appendix H. MatLab Code for Determination of Model Parameters of the ABR Process:

Function “lsqnonlin”

Objective function

$$\text{Minimize } F = \sum_{i=1}^n \left[\left(\frac{S_T}{S_{T0}} \right)_{i, \text{experiment}} - \left(\frac{S_T}{S_{T0}} \right)_{i, \text{prediction}} \right]^2 \quad (4.1)$$

Subject to

$$\frac{S_T}{S_{T0}} = \frac{(1-R)A + \frac{K_s}{S_{T0}}}{\mu_m t + A - 1} + R \quad (2.18)$$

$$R < 1$$

$$R, A, \mu_m, \text{ and } \theta > 0$$

where all parameters were the same as defined in Sections 2.2.1 and 4.5.1.

The parameters were set to $R = x(1)$, $A = x(2)$, $K_s = x(3)$, $\mu_m = x(4)$, lower and upper bounds of the parameters were set to (0, 0, 0, 0) and (1, 1000, 1000, 1000), respectively. The TOC effluent (S_T) concentrations of compartment 5 and the TOC influent concentrations (S_{T0}) of the ABR at different HRT are presented in Figure 4.6, which contributed to experimental values in Equation (4.1). The prediction values were determined by Equation (2.13).

- M-file

function f=myfun_parameters(x)

$$\begin{aligned} f = & (0.4064 - ((1-x(1))*x(2)+x(3)/948.3)/(x(4)*0.85/5+x(2)-1)-x(1))^2 + \\ & (0.1652 - ((1-x(1))*x(2)+x(3)/671.0)/(x(4)*1.73/5+x(2)-1)-x(1))^2 + \\ & (0.1212 - ((1-x(1))*x(2)+x(3)/968.6)/(x(4)*2.23/5+x(2)-1)-x(1))^2 + \\ & (0.1140 - ((1-x(1))*x(2)+x(3)/564.6)/(x(4)*2.66/5+x(2)-1)-x(1))^2 + \\ & (0.1011 - ((1-x(1))*x(2)+x(3)/973.3)/(x(4)*3.77/5+x(2)-1)-x(1))^2 \end{aligned}$$

- Invoke function “lsqnonlin”

$$x0 = [0.5, 0.1, 2, 2];$$

```
lb=[0,0,0,0];
ub=[1,1000,1000,1000];
[x,resnorm]=lsqnonlin(@myfun_parameters,x0,lb,ub)
```

- Export the results. The column of “x” corresponded to the value of R , A , K_s (mg/L), and μ_m (/day), respectively. The column of “resnorm” was the return of the values of residual at solution “x”.

```
x =
    0.0314    0.3758    2.0004    1.9099
```

```
resnorm =
    1.6032e-007
```

Appendix I. MatLab Code for Determination of the Total Hydraulic Retention Time and Total Electricity Cost of the ABR Process: Function “fmincon”

Objective function for the ABR process:

$$\text{Minimize: } F_{TotalElec} = F_{power} \left(\frac{1000 p_{ABR} t_{ABR}}{V_{ABR} (C_{TOC,i} - C_{TOC,e})} \right) \quad (4.6)$$

Subject to: (4.7)

$$\frac{S_T}{S_{T0}} = \left(\frac{0.39 + \frac{2.0}{S_{T0}}}{1.9t - 0.6} + 3.1 \times 10^{-2} \right) = \frac{C_{TOC,ei}}{C_{TOC,i}} = \left(\frac{0.39 + \frac{2.0}{C_{TOC,i}}}{1.9t_{ABR} / 24 - 0.6} + 3.1 \times 10^{-2} \right) \quad (4.2)$$

$$t_{ABR} \geq 12.7$$

$$C_{TOC,e} < C_{TOC,i} = 1000$$

$$C_{TOC,e} \leq 100$$

$$C_{TOC,i}, C_{TOC,e} \geq 0$$

where all parameters are the same as defined in Section 4.5.1.

- Parameters presented in the kinetic model Equations (4.19) and (4.20) are defined as follows.

$$\begin{aligned}
 F_{power} &= a \\
 p_{ABR} &= p \\
 C_{TOC,i} &= B \\
 V_{ABR} &= V \\
 \mu_m &= mu \\
 t_{ABR} &= x(1) \\
 C_{TOC,ei} &= x(2)
 \end{aligned}$$

- M-file of objective

```

function f=myoptimum_time(x)
a=0.055;           %in $/KWh;
p=80;             %in W
V=33.7;           %in L
B=1000;           %in mg/L
f=1000*a*p*x(1)/(V*(B-x(2)));

```

- M-file of constraints

```

function [c,ceq]=mycon_optimum(x)
B=1000;           %in mg/L
R=0.031;
A=0.4;
Ks=2.0;           %in mg/L
mu=1.9/24;        %in h
c=[];
ceq(1)=B*((1-R)*A+Ks/B)/(mu*x(1)+A-1)+R)-x(2);

```

- Invoking the function “fmincon”:

```

x0=[10,1];
lb=zeros(2,1);
A=[-1,0;0,1];
b=[-12.7;100];
options=optimset('largescale','off');
[x,fval]=fmincon(@myoptimum_time,x0,A,b,[],[],lb,[],@mycon_optimum,options)

```

- The results are shown as follows. The column of “x” corresponds to the values of the HRT of the ABR, the HRT of the UV photoreactor, the TOC effluent concentration of the ABR, and the TOC effluent concentration of the UV photoreactor, respectively.