PERFORMANCE EVALUATION OF AN UP- AND DOWN-FLOW ANAEROBIC REACTOR FOR THE TREATMENT OF POULTRY SLAUGHTERHOUSE WASTEWATER IN SOUTH AFRICA

BY

MOSES BASITERE

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Supervisor: Prof M.S. Sheldon

Co-supervisor: Prof S.K.O. Ntwampe

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Supervisors:

1. **Professor Marshal Shereene Sheldon (DTech; Pr. Tech.)**

Associate Professor: Chemical Engineering

Acting DVC Research, Technology, Innovation and Partnerships

Cape Peninsula University of Technology

Bellville Campus

Sheldonm@cput.ac.za

2. **Professor Seteno Karabo Obed Ntwampe (DTech; HDHET*)**

Associate Professor: Biotechnology

Acting HOD: Biotechnology and Consumer Science

Principal Investigator: Bioresource Engineering Research Group (*BioERG*)

Department of Biotechnology and Consumer Science

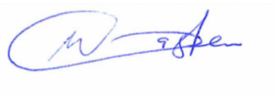
Cape Peninsula University of Technology

Cape Town Campus

NtwampeS@cput.ac.za

DECLARATION

I, **Moses Basitere**, declare that the contents of this thesis represent my own unaided work, except where specifically acknowledged in the text, and that the thesis has not previously been submitted for academic examination towards any qualification. Furthermore, this thesis represents my own opinions and not necessarily those of the National Research Foundation of South Africa or that of the Cape Peninsula University of Technology, or their sponsors.



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Moses Basitere Date:

ABSTRACT

The process of anaerobic digestion (AD) is one of the most cost-effective and environmentally sustainable technologies to treat wastewater in the agricultural sector. In South Africa, in some industries in the agricultural sector, such as the poultry industry in particular, slaughterhouses have the highest consumption of potable water, culminating in the production of a large quantity of high strength wastewater. This high consumption of potable water has become a concern in South Africa due to water scarcity and reduced rainfall attributed to global warming, including weather changes. Furthermore, the generation of a large volume of wastewater poses environmental pollution concerns. The wastewater from poultry slaughterhouses can be quite easily treated to a suitable quality for reuse, using various bioreactor systems that utilise low cost anaerobic digestion processes. However, as this wastewater contains a high quantity of biodegradable organic matter – with the primary pollutants being proteins, blood, fats, oil and grease (FOG) – selecting a suitable anaerobic reactor configuration (up-flow vs down-flow) plays an important role in achieving high reactor performance. In this study, both the up-flow, (i.e. Expanded Granular Sludge Bed Reactor) and the down-flow (i.e. Static Granular Static Granular Bed Reactor), were studied to quantitatively determine their performance in treating poultry slaughterhouse wastewater.

Firstly, the feasibility of treating poultry slaughterhouse wastewater with an up-flow Expanded Granular Sludge Bed Reactor (EGSB) coupled with anoxic and aerobic bioreactors was investigated at an HRT of 7 (168 hr), 4 (96 hr) and 3 (72 hr) days using organic loading rates of 0.5, 0.7 and 1.0 gCOD/L.day. The averaged tCOD removal for the EGSB reactor was 40%, 57% and 55%, respectively, at the various OLRs and HRTs investigated. The overall tCOD removal of the system (EGSB-anoxic/aerobic) at high OLR of 1.0 gCOD/L.day was increased to 65%. The redundant performance of the up-flow EGSB reactor was attributed to the periodical sludge washout experienced during its operation due to high FOG and TSS concentrations in the influent. Due to the periodic sludge washout, the reactor required continuous re-inoculation resulting in the EGSB being operated for a short period (i.e. 26 days). As a result of such system deficiency, it was recommended that to improve the performance of the up-flow EGSB reactor in treating poultry slaughterhouse wastewater, a pre-treatment system – such as a Dissolved Air Floatation system (DAFs) or a FOG skimmer – is required to reduce the FOG and

total suspended solids (TSS) load prior to the wastewater fed to the EGSB. This will minimise system failure and the need for a continuous re-inoculation of the system (see Appendix C for improved operation strategy of the EGSB reactor). Furthermore, a system redesign was recommended, thus the use of the SGBR.

Secondly, after the EGSB system evaluation, the performance of a down-flow system (i.e. SGBR) for the new design, the following were deemed appropriate for improved system (SGBR) design: 1) reduced HRT for high wastewater treatment through-put rates; 2) the ability to adequately treat the wastewater with higher organic loading rates; and 3) reduction of the plant footprint by using a membrane filtration system (i.e. a single process unit) to effectively reduce process requirements needed for the anoxic/aerobic bioreactors (i.e. n=2 process unit) used with the EGSB. Similarly, for large-scale operations, it is advisable to have a backwash system to adequately handle declogging processes (i.e. these systems modifications were evaluated in the SGBR).

The SGBR, coupled with an ultra-filtration (UF) membrane system, was then investigated for treating the poultry slaughterhouse wastewater at an HRT of 55 hrs and 40 hrs, including average OLRs of 1.01 and 3.14 gCOD/L.day, respectively. The average maximum performance of the SGBR in terms of tCOD, TSS and FOG removal was > 90% at the OLRs and HRTs investigated. The UF membrane system used as a post-treatment system further yielded a system performance improvement for tCOD, TSS and FOG of 64%, 88% and 60%, respectively. The overall performance of the combined system (SGBR and UF membrane system) in terms of tCOD, TSS and FOG removal was 98%, 99.8% and 92.4%, respectively. The highest performance for the down-flow SGBR was attributed to its ability to retain granulated sludge in the reactor while maximizing the digestion of the organic matter fed into the reactor, even at higher OLRs. Furthermore, for effective declogging, the implementation of a periodic backwash system to effectively remove dispersed fine sludge particles in the underdrain and excessive suspended solids entrapment was observed to ease the system operational deficiencies.

Due to the high performance of the down-flow SGBR, in comparison to the up-flow EGSB (i.e. for the treatment of poultry slaughterhouse wastewater), an experimental re-run was conducted with a working volume of 2L SGBR, using different HRTs (n=4)

(90hr, 55 hr, 48 hr and 36 hrs). The system was operated over a period of 110 days at an OLR range of 0.623 to 7.806 gCOD/L to obtain sufficient data for kinetic modelling of substrate removal from the SGBR. Furthermore, kinetic models used for predicting tCOD removal were only evaluated for the SGBR due to its performance, using both the modified Stover-Kincannon and Grau second-order models, to quantitavely determine the systems kinetic parameters. Overall, for process control evaluations and to assess whether or not a system is performing according to design specifications, models are required to describe the performance of a desired system.

For this study, a significant correlation between the predicted and experimental data was not found for either the Grau second-order or the modified Stover-Kincannon models. Additionally, the predicted data was usually higher than the experimental data, with high variation observed between the predicted and experimental data at a reduced HRT of 36 hr and average loading rate of 4.10 gCOD/L for both the Grau and the modified Stover-Kincannon models when the system was fed with undiluted poultry slaughterhouse wastewater. The high variation between the experimental and the predicted data at high OLRs might have been due to unaccounted operational deficiencies by the models, which resulted in an increase head lose through the granular bed due to the accumulation of excess biomass and the retained solids, alleviated by periodic backwashing of the system. Even with such operational deficiencies, the SGBR system maintained its high overall COD removal rates regardless of changes in OLRs and HRTs, with an overall average tCOD removal of 82% achieved

Keywords: Poultry slaughterhouse wastewater, Expanded Granular sludge-bed reactor (EGSB), Static Granular bed reactor (SGBR).

DEDICATION

This thesis is dedicated to my parents,

Mr Chiawelo Basitere and Mrs Elelwani Basitere,

and

my late grandmother,

Mrs Thinavhuyo Basitere

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RESEARCH OUTPUTS

The following research outputs represent the contributions by the candidate to scientific knowledge and development during his doctoral candidacy **(2014-2017):**

The following DHET-accredited research articles and conference proceedings were published from the studies reported in this thesis:

I. **Basitere, M.**, Williams, Y., Sheldon, M.S., Ntwampe, S.K.O., De Jager, D. & Dlangamandla, C. 2016. Performance of an expanded granular sludge bed (EGSB) reactor coupled with anoxic and aerobic bioreactors for treating poultry slaughterhouse wastewater. *Water Practice Technology,* 11 (1):86-92 (DOI: 10.2166/wpt.2016.013).

II. **Basitere, M.**, Rinquest, Z., Njoya, M., Sheldon, M.S. & Ntwampe, S.K.O. 2017. Treatment of poultry slaughterhouse wastewater using a static granular bed reactor (SGBR) coupled with ultrafiltration (UF) membrane system. *Water Science and Technology*, 76(1):106-114 (DOI:10.2166/wst.2017.179).

III. **Basitere, M.**, NJoya, M., Rinquest, Z., Sheldon, M.S. & Ntwampe, S.K.O. 2017. Performance and kinetic analysis of a static granular bed reactor for treating poultry slaughterhouse wastewater. In *Frontiers International Conference on Wastewater Treatment and Modelling*, 225-229. Springer, Cham (Available Online 05 May 2017; DOI: 10.1007/978-3-319-58421-8_35.

The following DHET- accredited research articles were published from previous studies related to this thesis:

IV. Dlangamandla, C., Dyantyi, S.A., Mpentshu,Y.P., Ntwampe, S.K.O. & **Basitere, M.** 2016. Optimization of bioflocculant production by a biofilm forming microorganism from poultry slaughterhouse wastewater for use in poultry wastewater treatment. *Water Science and Technology,*: wst2016047.

The following research articles, based on research studies reported in this thesis, are under review:

V. **Basitere, M.**, Njoya, M., Sheldon, M.S. & Ntwampe, S.K.O. Review: up-flow vs down-flow anaerobic digester reactor configurations for treatment of fats-oil-grease laden poultry slaughterhouse wastewater: **Submitted to the *Water Journal*** (Manuscript ID: Water-190978).

VI. **Basitere, M.**, NJoya, M., Rinquest, Z., Sheldon, M.S. & Ntwampe, S.K.O. 2017. Kinetic analysis and performance evaluation of a static granular bed reactor for treating poultry slaughterhouse wastewater. **Submitted to Water Practice and Technology** (Manuscript ID: WPT-17-129).

VII. Dlangamandla, C., Ntwampe, S.K.O. & **Basitere, M.** A bioflocculant supported dissolved air flotation system for removal of suspended solids, lipids and protein matter from poultry slaughterhouse wastewater. **Submitted to the *Water Science and Technology*** (Manuscript ID: WST-EM17887)

The following International conference presentations were delivered for research studies related to this thesis:

VIII. **Basitere, M.**, Williams, Y., Sheldon, M.S., Ntwampe, S.K.O., De Jager, D. & Dlangamandla, C. Performance of an Expanded Granular Sludge Bed (EGSB) reactor coupled with anoxic and aerobic bioreactors for treating poultry slaughterhouse wastewater*, 7th Eastern Europe Young Water Professional, Belgrade, Serbia, 17-19, September 2015.*

IX. **Basitere, M.,** Rinquest, M., Njoya, M., Sheldon, M.S. & Ntwampe, S.K.O. 2016. Treatment of poultry slaughterhouse wastewater using a Static Granular Bed Reactor (SGBR) coupled with Ultrafiltration (UF) membrane. 13th IWA Specialized Conference on Small water and waste water systems (SWWS), Athens, Greece, 13-18 Sep 2016.

X. **Basitere, M.,** NJoya, M., Sheldon, M.S. & Ntwampe, S.K.O. Performance and kinetic analysis of a Static Granular Bed Reactor for treating poultry slaughterhouse wastewater. Frontiers International conference of wastewater treatment, 21-24 May 2017, Palermo, Italy.

LAYOUT OF THESIS

This research study was conducted at the Department of Chemical Engineering, Cape Peninsula University of Technology, Cape Town campus, South Africa.

The thesis was divided into the following chapters:

Chapter One: This chapter briefly discusses the background and motivation of the study; the problem statement; the research questions, aim and objectives; hypotheses; and finally, the delineation of the study.

Chapter Two: This chapter focuses on the literature reviewed, presenting a detailed overview of the Up-flow Expanded Granular Sludge Bed (EGSB) reactor in comparison to the down-flow Static Granular Bed Rector (SGBR) which are used as anaerobic digesters. The literature review highlighted challenges faced by both EGSB and SGBR in the treatment of fats, oil, and grease (FOG) laden poultry slaughterhouse wastewater.

Chapter Three: This chapter focuses on a brief overview of kinetic models used in the modelling of anaerobic digestion system used in wastewater treatment (i.e. models which were subsequently used in this study).

Chapters Four: This chapter focused on the evaluation of the performance of the Up-flow Expanded Granular Sludge Bed (EGSB) reactor coupled with anoxic and aerobic bioreactors in treating poultry slaughterhouse wastewater. Challenges observed during the operation of the laboratory-scale EGSB in treating the FOG-laden poultry slaughterhouse wastewater are also discussed. Supplementary data on the improved operational strategy of the EGSB reactor is enlisted in Appendix C.

Chapter Five: This chapter focused on the evaluation of the performance of the Down-flow Static Granular Bed Reactor (SGBR) coupled with an ultrafiltration membrane system for the treatment of poultry slaughterhouse wastewater. Challenges faced during the operation of the down-flow anaerobic digestion were also discussed. Supplementary data for this chapter is enlisted in Appendix B.

Chapter Six: This chapter was a re-run of the SGBR reactor system used in Chapter Five, operated at various OLRs and HRTs with a focus on evaluating the bio-kinetic model parameters for the SGBR treatment of poultry slaughterhouse wastewater, a system determined to have a better performance than the EGSB in treating poultry slaughterhouse wastewater.

Chapter Seven: This chapter contains the summary of the research, with recommendations for future studies offered.

Bibliography: The consulted literature and all cited material listed in this section is presented in accordance with the specified requirements for referencing.

Appendices: Supplementary data are enlisted in this section. Furthermore, the supplementary data from each chapter, forming part of this thesis, are highlighted with an exposition where required.

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LIST OF SYMBOLS

Nomenclature

Symbol	Description	Units
A	Disc surface area	m^2
E	Removal efficiency	-
K_B	Stover-Kincannon saturation constant	g/L.day
K_d	Endogeneous decay coefficient	1/day
k_s	Grau substrate removal rate constant	1/day
K_s	Monod’s half velocity constant	mg/L
S_0	Influent substrate concentration	gCOD/L
S_e	Effluent substrate concentration	gCOD/L
Q	Flow rate	L/day
V	Working reactor volume	L
U_{max}	Maximum rate of substrate utilisation	g/L.d
X	Average biomass concentration	g VSS/L
X_0	Influent biomass concentration	g VSS/L
X_E	Effluent biomass concentration	g VSS/L
Y	Growth yield coefficient	VSS/gCOD

Greek symbols

Symbol	Description	Units
θ_H	Hydraulic retention time	day
θ_c	Solids retention time	day
μ	Specific growth rate	1/day
μ_{max}	Maximum specific growth rate	1/day

ABBREVIATIONS

BOD_5	-	Biochemical oxygen demand
CIP	-	Cleaning-In-Place
sCOD	-	Soluble chemical oxygen demand
tCOD		Total chemical oxygen demand
CPUT	-	Cape Peninsula University of Technology
DOC	-	Dissolved organic carbon
ECS	-	Extra capillary space
EGSB	-	Expanded granular sludge-bed
GAC	-	Granular activated carbon
HRT	-	Hydraulic retention time
HLT	-	Hydraulic loading rate
MBR	-	Membrane bioreactor
NF	-	Nano-filtration
FOG	-	Fats, oil and grease
OLC	-	Organic loading concentration
PhAC	-	Pharmaceutical compounds
PSW	-	Poultry slaughterhouse wastewater
SA	-	South Africa
SO_3^-	-	Sulphide ions
SRT	-	Solid retention time
SS	-	Suspended solids
TDS	-	Total dissolved solids
TOC	-	Total organic carbon
TSS	-	Total suspended solids
UASB	-	Up-flow anaerobic sludge-bed
UF	-	Ultra-filtration
VSS	-	Volatile suspended solids
VFA	-	Volatile fatty acid
WWTP	-	Wastewater treatment plant

CHAPTER ONE

INTRODUCTION

1. INTRODUCTION

1.1 Background of the research problem

A common problem facing the poultry industry globally is an increase in potable water usage due to an increase in the production of poultry products culminating in the generation of high strength wastewater (Apha, 1965; Kiepper *et al*., 2008). Generally, poultry processing plants consume an average of 26.5 L/bird of potable water during the primary and secondary processing of live birds to meat (Yordanov, 2010). Most of the potable water is used for scalding, defeathering, evisceration and sanitation of equipment (Yordanov, 2010, Avula *et al*., 2009). An estimated 2 to 5% of total proteins, including carcass debris and FOG from the carcass, are lost into the wastewater stream, resulting in high strength wastewater with a higher concentration of biological oxygen demand (BOD_5) and chemical oxygen demand (tCOD) as compared to domestic wastewater (Zhang *et al*., 2006). This is indicative of the need for an intensive treatment process *prior* to the water being discharged into the environment, into receiving water bodies such as rivers and dams (Plumber & Kiepper, 2011). Due to an increasingly stringent regulatory environment, both globally and nationally, coupled with water supply insecurities including the imminent water scarcity in South Africa (SA), poultry product processing industries must develop advanced treatment systems for their wastewater to mitigate against these current water shortages. The treatment of wastewater will thus benefit poultry processing plants by reducing potable water demand and the volume of wastewater generated for disposal (Avula *et al*., 2009).

Traditional anaerobic treatment systems – such as anaerobic digesters, anaerobic contact process systems and anaerobic lagoons – have been applied successfully in the food processing industry for treating wastewater (Avula *et al*., 2009). These systems have been used for the reduction of tCOD and BOD_5 concentrations which stabilise the wastewater treatment system used through sludge retention. Furthermore, anaerobic treatment systems, such as an up-flow anaerobic sludge-bed (UASB), popularised the use of granulated anaerobic biomass reactor systems, representing a significant improvement in wastewater treatment from traditional systems previously employed in the wastewater treatment industry (Oh, 2012). Further development and design of anaerobic digesters which produced systems such as the Expanded Granular Bed Reactor (EGSB), a modification of UASB, have demonstrated the capability to propagate sludge granules to effectively increase contact between the wastewater and granules, facilitated by recirculation streams which result in an increased up-flow velocity and thus granular-bed expansion for sustainable system performance (Oh, 2012). Furthermore, the UASB and the EGSB reactor performances are dependent on a well-designed gas-liquid-solids separation (GLSS) system to separate the biogas phase from the wastewater and biomass. Finally, another anaerobic digester, namely the Static Granular Bed Reactor (SGBR), a simplified down-flow high rate, low cost anaerobic granular system, has provided further high performance in treating high strength wastewater (Park *et al*., 2012). Unlike the UASB and EGSB reactors which require gas-liquid-solids separation (GLSS), the SGBR uses an underdrain system to retain the biomass (Oh, 2012; Park *et al*., 2012).

For this study, both the up-flow EGSB coupled with anoxic-aerobic bioreactors and the down-flow SGBR coupled with a UF membrane system were evaluated for the reactors' performances in reducing organic matter in the poultry slaughterhouse wastewater. A poultry processing company located in the Western Cape Province of Cape Town, South Africa, was chosen for this study as the industrial partner to supply fresh poultry slaughterhouse wastewater. This study was conducted using a constructed laboratory-scale plant on the Cape Town campus of the Cape University of Technology (CPUT).

1.2 Problem statement

Poultry slaughterhouse wastewater (PSW) contains high BOD_5 and tCOD due to the presence of proteins, FOG, and carbohydrates from meat, blood, skin and feathers. Due to its high soluble and particulate matter, PSW requires treatment to meet the South African Government industrial effluent discharge standards for minimizing the pollution load borne by receiving water bodies.

1.3 Research questions

- How efficient and effective is a combination of an up-flow EGSB reactor with anoxic and aerobic bioreactors in reducing the high level of soluble and particulate matter, including other constituents, in the poultry slaughterhouse wastewater? (Chapter Four)
- How efficient and effective is a combination of a down-flow SGBR reactor with an UF membrane system as a post-treatment in reducing the high level of soluble

and particulate matter, including other constituents, in the poultry slaughterhouse wastewater? (Chapter Five)

- Does the quality of the treated wastewater, either recovered from the up-flow EGSB with anoxic-aerobic configuration or the down-flow SGBR with an UF system, meet the South African municipal discharge standard? (Chapters Four & Five)
- Once treated, is it feasible to re-use the water reclaimed from either the up-flow or down-flow EGSB and SGBR? (Chapters Four & Five)
- Is there a need for an additional process unit for the treated water to either meet the discharge standards or for re-use? (Chapters Four & Five)

1.4 Aim of the study

The aim of this study was to evaluate the performance of anaerobic reactor configurations (up-flow EGSB and down-flow SGBR) for the treatment of poultry slaughterhouse wastewater to meet the City of Cape Town's discharge standards and also to assess the efficacy of further treatment stages (anoxic-aerobic for the EGSB or UF membrane for the SGBR) for the re-use of the treated wastewater.

1.5 Hypotheses

The down-flow configuration of the static granular bed reactor (SGBR) will be able to treat high strength PSW, achieving a high performance in comparison to an up-flow expanded granular sludge bed (EGSB) reactor. Furthermore, it is hypothesized that the best anaerobic reactor configuration (down-flow or up-flow) to treat PSW with high performance rate will be dependent on its ability to retain sludge in the reactor during operation.

1.6 Objectives

The objectives for this study were as follows:

a) to evaluate the effectiveness of the up-flow-flow EGSB reactor coupled with anoxic-aerobic tank configuration in treating poultry slaughterhouse wastewater;

b) to evaluate the effectiveness of the down-flow SGBR coupled with an UF membrane system in treating poultry slaughterhouse wastewater;

c) to determine the bio-kinetic parameters, which can be used to predict tCOD removal from a suitable anaerobic reactor configuration in either (a) or (b) depending on the reactor performance for each system;

d) to investigate if there is a need for a pre-treatment stage prior the anaerobic digestion stage to improve the performance of the reactor in both EGSB and SGBR configurations; and

e) to identify limitations of both reactor configurations (a) and (b) for the treatment of poultry slaughterhouse wastewater.

1.7 Delineation of the study

While biogas generation plays a major role in an anaerobic reactor's performance, this study did not report on the biogas production due to design challenges faced during reactor operation, particularly with the measuring equipment for the prevention of reporting on inconsistent data. This study focused primarily on the performance of the EGSB reactor and SGBR in treating poultry slaughterhouse wastewater, not that from other slaughterhouses or abattoirs. Furthermore, the use of UF membrane system in the SGBR configuration set-up was limited to assessing the suitability of membrane systems and did not include the evaluation of various membrane types.

CHAPTER TWO

LITERATURE REVIEW

Submitted as: **Basitere, M.**, Njoya, M., Rinquest, M., Sheldon, M.S. & Ntwampe, S.K.O. Review: Up-flow vs down-flow anaerobic digester reactor configurations for treatment of fats-oil-grease laden poultry slaughterhouse wastewater: Submitted to the **Water Journal**, **Manuscript ID: Water-190978.**

2 . REVIEW: UP-FLOW VS DOWN-FLOW ANAEROBIC DIGESTER REACTOR CONFIGURATIONS FOR TREATMENT OF FATS-OIL-GREASE LADEN POULTRY SLAUGHTERHOUSE WASTEWATER

2.1 Introduction

The agricultural sector consumes a large quantity of freshwater resources, with a global average usage exceeding 70% of all surface water (Bustillo-Lecompton *et al*., 2016). This increase in water utilization in the agricultural sector poses severe environmental challenges due to water pollution, as large quantities of wastewater is generated (Bustillo-Lecompte & Mehrvar, 2015; Bustillo-Lecompte *et al*., 2016), further exacerbating the already detrimental environmental pollution. Some industries in the agricultural sector, such as poultry processing facilities like slaughterhouses, utilize a large quantity of freshwater which culminates in the generation of large volumes of wastewater with the potential to pollute freshwater sources if not treated appropriately prior to discharge into receiving waters such as rivers (Gerber *et al*., 2007). This problem is endemic in developing countries such as South Africa (SA) where monitoring to ensure compliance is lacking.

Microbial wastewater treatment technologies such anaerobic digestion (AD) can play a vital role in remedying the environmental concerns posed by poultry slaughterhouse wastewater (PSW) generation. The process of AD is considered the most appropriate wastewater treatment technology suitable and presently available for the treatment of PSW. This type of technology has been used for treatment of industrial wastewater such as paper mill effluent (Sheldon *et al*., 2012), textile wastewater (De Jager *et al*., 2012), soft drink wastewater (Sheldon & Erdogan, 2016) and domestic wastewater (Lim, 2009; McCarty & Smith, 1986). Historically, the AD process has been regarded as most appropriate for treatment of wastewater in large-scale operations. Currently, it remains the preferred treatment method in the food waste (FW) industry due to its numerous advantages such as low energy consumption, reduced production of waste biological solids, low nutrients and chemical requirements, high tCOD reduction, pathogen deactivation even at high loading rates, including the production of biogas which can be combusted to generate heat and electricity or refined into renewable natural gas and other fuels (Bustillo-Lecompte & Mehrvar, 2015; Bustillo-Lecompte *et al*., 2016).

However, AD also has some disadvantages: it is highly sensitive to pollutants which reduce metabolic functions of organisms constituting the sludge biomass, odour production during operation, and an elongated start-up procedure which can be difficult to stabilize when operated by semi-skilled personnel. Moreover, the resultant treated wastewater might require further post-treatment (using tertiary treatment systems) for the effluent from the process to meet regulatory discharge standards (Harris & MaCabe, 2015; Lim, 2009). Generally, though, AD is a robust and stable treatment reactor if the system operation is well-understood (Lim, 2009). Furthermore, the AD process can play a vital role in waste management and in the reduction of greenhouse gas emissions (Harris & MaCabe, 2015) and the digestate can be used as value-added organic fertilizer for soil amendment (Lim, 2009).

Generally, the high strength PSW in South Africa is characterized by 35% more proteins, resulting in high tCOD ranging from 2133-10655 mg/L, BOD_5 ranging from 1100-2750 mg/L and FOG in the range of 131 to 684 mg/L (refer to Chapter Five). While the AD process is effective in the degradation of other substrates in PSW, FOG presents several challenges, such as its accumulation in pipe walls leading to pipe blockages (Harris *et al*., 2015). This review highlights best practices when selecting an anaerobic digestion reactor configuration (down-flow vs up-flow), in particular for the treatment of PSW with a high fats-oil-grease (FOG) content. Additionally, various challenges are highlighted for using each of these reactor configurations.

2.2 Overview: poultry slaughterhouse water usage, wastewater generation and environmental impact

Poultry processing plants involve the processing of live birds into numerous consumable meat products (Avula *et al*., 2009). Poultry product processing steps are divided into three categories, namely: 1) bird slaughtering, de-feathering and the evisceration of the poultry carcass to produce whole birds; 2) cutting of the carcasses into various parts and deboning; and 3) the production of value added food for consumers (Kiepper *et al*., 2008; Avula *et al*., 2009). The critical control point in the poultry processing facility for reducing the contamination of the products is the evisceration process, in particular for limiting and/or eradicating any leakage from the birds' guts, as these harbour pathogens. A visual inspection is conducted to segregate carcasses that might be exposed to the gut contents (i.e. faecal matter) or birds suspected of contamination by other contaminants which culminates in the necessary implementation of reprocessing procedures. During this process, there is a potential for coliforms such as *Escherichia coli* and *Salmonella* sp. to contaminate bird carcasses (Shih & Kozink, 1980; Avula *et al*., 2009). The contaminated carcasses should be washed prior to trimming. Furthermore, temperature should be controlled to minimize proliferation of pathogens in the edible parts of the bird (Avula *et al*., 2009). Overall, including this washing, poultry slaughterhouse water usage per bird and wastewater generated can be substantial, resulting in product and environmental contamination if such a processing facility does not adhere to adequate preventative measures like waste handling facilities and wastewater treatment processes.

2.3 Average water usage per bird

Poultry slaughterhouse industrial plants use relatively high quantities of potable water, with an average of 26.5 L/ 2.3 kg bird during the primary and secondary processing of live birds to meat (Avula *et al*., 2009). During the initial stages, freshwater usage is for bleeding and scalding processes whereby the water is used to wash off blood subsequent to the immersion of the bird into hot water at a temperature of 50ºC to ease defeathering (Bustillo-Lecompte & Mehrvar, 2015). Thereafter, water is for rinsing the scalded carcass with rotating and pressurized water jets. Subsequently, chilling of the bird to 4 °C occurs – a process which, naturally, involves the immersion of the carcass into chilled water (Bustillo-Lecompte & Mehrvar, 2015). The chiller requires an average of 1.9 L/bird of potable water, using, then, approximately 475,000 L/day of process water in a plant that process 250,000 birds/day (Shih & Kozink, 1980; Avula *et al*., 2009). Overall, water is necessary for bird wash, chilling, evisceration, cutting/deboning and packaging, as indicated in Figure 2.1.

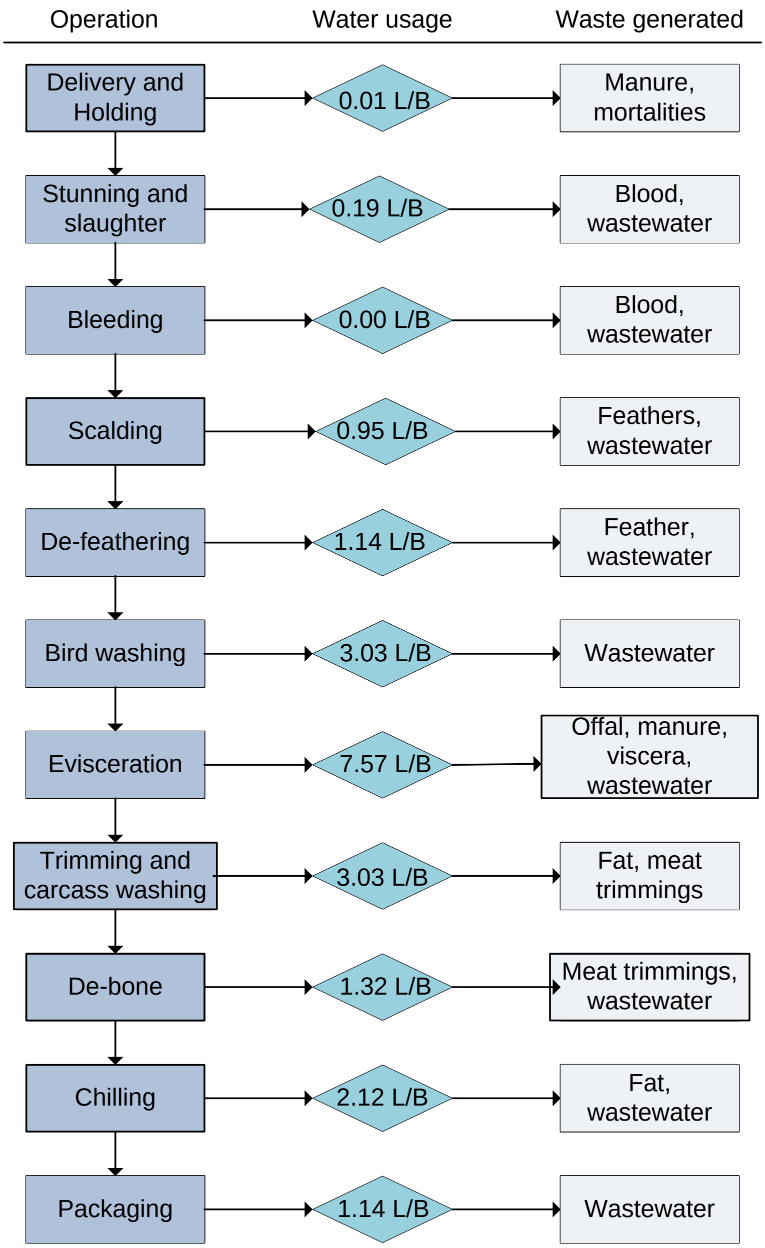

Figure 2.1: Average water usage per bird during processing (Avula *et al*., 2009)

Furthermore, water is also used as a transport medium for the by-products of slaughtering (for example, for the mobilization of offal including feathers, heads and viscera) (Avula *et al*., 2009). Yet another significant pollutant in the poultry process water is residual protein from carcass debris, blood, fats, oil and grease (FOG) and feathers (Avula *et al*., 2009; Yordanov, 2010). The poultry process wastewater contains predominantly 35% protein, resulting in a much higher BOD_5 and tCOD observed in the wastewater from such facilities as compared to municipal sewerage (Zhang *et al*., 1997; Avula *et al*., 2009).

2.4 Poultry wastewater generation and its impact on environmental health

The discharge of wastewater into the environment from poultry slaughterhouses in SA has developed into a significant environmental concern (Steinfeld *et al*., 1998). Other processes which utilize a sizeable quantity of water are associated with the cleaning of equipment and surfaces for sanitation (Gerber *et al*., 2007). The wastewater generated during these activities also has a high BOD_5 and tCOD due to other constituents such as nitrogen, phosphorous and disinfection by-products, when chemicals such as chlorine are used during sanitization procedures (Gerber *et al*., 2007). Furthermore, the wastewater contains a variety of microbial contaminants including Campylobacter sp. among others (Sims & Wolf, 1994).

PSW was estimated to contain 6.8 kg BOD_5 per ton live weight killed (LWK) and 3.5 kg suspended solids (SS) per ton of LWK (De Haan *et al*., 1997). This suggests that if the PSW is not appropriately treated prior to discharge, it can potentially pollute land and surface water, posing as a serious risk to human health (Sims & Wolf, 1994). The biodegradable organic compounds in PSW can cause a reduction in dissolved oxygen (DO) in surface waters, potentially leading to death of aquatic life (De Haan *et al*., 1997). Additionally, the presence of macronutrients in the wastewater, such as phosphorous and nitrogenous compounds, has the potential to facilitate eutrophication in PSW contaminated surface water bodies (Gerber *et al*., 2007). The subsequent algal growth and mineralization of algae has the potential for a further deleterious cumulative effect on aquatic life due to the depletion of DO which is consumed during algal proliferation in contaminated waters (Bustillo-Lecompte & Mehrvar, 2015).

2.5 Composition of poultry slaughterhouse wastewater

Table 2.1 lists an average range of characteristics for PSW obtained from the poultry slaughterhouse located in the Western Cape of SA: parameters quantified over a 9-week sampling period from several poultry product-processing facilities.

Table 2.1: Characteristics of poultry slaughterhouse wastewater in the Western Cape, South Africa (quantified as part of this study, as minimal published data is available in SA)

Parameter(s)	Unit	Range	Average
pH		6.5-8.0	6.88
Alkalinity	mg/L	0- 489	489
Total chemical oxygen demand	mg/L	2133-10655	6394
Soluble chemical oxygen demand	mg/L	595-1526	972
Biological oxygen demand	mg/L	1100-2750	1667
Total Kjheldahl Nitrogen	mg/L	77-352	211
Ammonia	mg/L	29-51	40
Total Phosphorus	mg/L	8 – 27	17
Fats, oil and grease	mg/L	131-684	406
Total dissolved oxygen	mg/L	372-936	654
Total suspended solids	mg/L	315-1273	794
Volatile suspended solids	mg/L	275-1200	738
Soluble proteins	mg/L	0-368	72
Volatile fatty acids	mg/L	96-235	235

2.6 Legislation governing discharge of poultry slaughterhouse wastewater (PSW) in South Africa (SA)

In SA, regulation of water, wastewater management practices and industrial discharge standards are governed by the National Water Act (Act 36 of 1998) and the Water Services Act (Act 108 of 1997), respectively. The Department of Water Affairs (DWA) developed the Waste Discharge Charge System (WDCS) consisting of two distinct charges – the waste mitigation charge and waste discharge levy – established under the National Water Act of 1998 and primarily aimed at providing economic incentives and penalties to encourage water conservation and water use minimization practices (DWA, 2012; CSIR, 2010). Parameters such as salinity, electrical conductivity (EC), chloride, sodium, sulphate (SO_4^{2-}), nutrients (soluble phosphorous (PO_4^{3-}), nitrates (NO_3^-), ammonium (NH_4^+), heavy metals (arsenic, cadmium, chromium, copper, mercury, lead, nickel, zinc), organic matter (BOD_5 and tCOD), and pH, are taken into consideration by the WCDS.

As a consequence of the WCDS, poultry slaughterhouses that have been granted permission to discharge wastewater into municipal sewer systems are required to abide by local municipal by-laws for each municipality, as prescribed by the Water Services Act of 1997 (CSIR, 2010: Molapo, 2009). Poultry slaughterhouses located in the SA’s Western Cape must therefore, comply with the City of Cape Town Wastewater (CCT) and Industrial Effluent By-law (2013). The associated discharge rates are calculated in accordance with Schedule 1 of this by-law and the tariff by-law of the CCT. Additionally, municipalities enforce surcharges for transgressions, with slaughterhouses penalised when their PSW does not meet the required discharge standards, including volumes. The maximum limits of permitted discharge into municipal sewers in accordance with Schedule 1 of the CCT by-law are summarised in Table 2.2 (City of Cape Town, 2014). The implementation of suitable wastewater treatment methods is therefore highly recommended, with some of the suggested PSW treatment technologies used to generate biogas to use as a source of energy.

Table 2.2: South African industrial discharge (DWA 2010), SANS 241 (2015) drinking standard and municipal discharge standards (Western Cape & Mangaung)

		DWA 2010	SANS 241	Western Cape	Mangaung
Parameter	Units	General limit	Operational limits	Not to exceed	Operational limits
Temperature at point of Entry	ºC	-	-	40	44
Conductivity	mS/m	70-150	<150	500	500
pH at 25ºC	-	5.5-9.5	5.5-9.5	12	10
COD	mg/L	75	-	5000	5000
SS	mg/L	25	-	1000	1000
TDS at 105ºC	mg/L	-	<1000	4000	4000
Total sulphates (SO_4^{2-})	mg/L	-	<400	1500	1500
O&G	mg/L	2.5	-	400	400
TP	mg/L	10	-	25	25
Faecal coliforms (per 100mL)		1000	-	-	-
Turbidity	NTU	-	<1.0	-	-
Ammonia as Nitrogen	mg/L	-	<1.0	-	-
DOC	mg/L	-	<10	-	-
Nitrates	mg/L	15	-	-	-

2.7 Anaerobic digestion treatment

2.7.1 Anaerobic degradation pathways and biogas generation

An anaerobic digestion process is a biochemical process that occurs in the complete absence of free molecular oxygen (Judd, 2010). During the anaerobic wastewater treatment process, neither oxygen nor nitrates serve as the terminal electron acceptor (Massé & Droste, 2000), while organic compounds such as sulphates and ferric compounds serve as anaerobic electron acceptors. The redox potential of an anaerobic system lies between -300 mV and -400 mV, an indication of a reducing environment (Massé & Droste, 2000). The process of AD for an organic complex involves both chemical and biological processes, as shown in Figure 2.2.

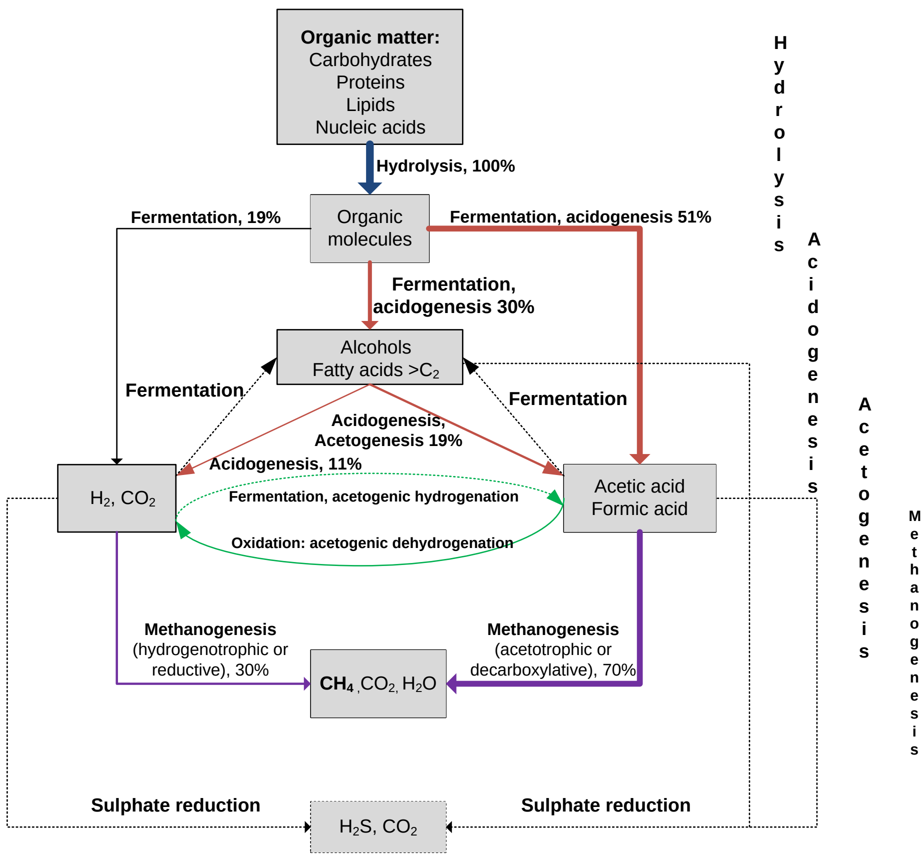

Figure 2.2: Schematic illustration of the different metabolic steps and microbial groups involved in the complete degradation of organic matter (Van Haandel & Lettinga, 1994; McInerney, 1999; Poulsen, 2003)

Metabolic processes in AD involve the decomposition of organic molecules into simple soluble compounds (amino acids, glucose and long chain fatty acids) by a process known as *hydrolysis* (Gerardi, 2003). Extracellular enzymes excreted by hydrolytic and fermentative bacteria carry out the hydrolysis process, the rate-limiting step of the overall AD process (Massé & Droste, 2000). Hydrolysed organic molecules are fermented into alcohol and volatile fatty acids (VFA) (i.e. short chain fatty acids such as acetate, propionate and butyrate) in a process known as *acidogenesis* (McInerney, 1999). During the acidogenesis process, short-chained fatty acids are degraded into acetate, hydrogen and carbon dioxide (CO_2), by hydrogen (H_2) producing acetogenic bacteria. Furthermore, about 66% of long chain fatty acids are oxidized into acetate, while 33% to H_2 gas through a process known as *acetogenesis* (Poulsen, 2003). The acetate is converted in the final stage into CO_2 and methane (CH_4) by acetoclastic methanogens. Generally, 70% of the produced methane gas is from the acetate and 30% from CO_2 reduction by hydrogen oxidizing methanogens (Gerardi, 2003). The methane produced can be used as an energy source to replace fossil fuels and reduce carbon dioxide emissions, contributing to the reduction of greenhouse gas production. However, reactor configuration for AD influences overall operability including treatment efficiency, depending on the volume and quality of the PSW being treated, particularly PSW with a high FOG concentration.

2.7.2 Operating factors that affect anaerobic digestion process

(a) Temperature, volatile and alkalinity ratio

Temperature plays a critical role in the maintenance of optimum operation of anaerobic digestion and biogas production. The temperature must be maintained uniformly throughout the anaerobic digester to prevent localised pockets of depressed temperature and undesired bacterial activity (Geradi, 2003; Song *et al*., 2016). Variation of temperature within the AD has the potential to affect biological activity, culminating in the inhibition of methane forming bacteria (Song *et al*., 2016). Methane forming bacteria (methanogens) are normally active in a mesophilic temperature of 30 to 35^{o}C and thermophilic temperature of 50 to 60^{o}C (Geradi, 2003). The inhibition of the methanogens occurs at a temperature of 40 to 50^{o}C. The minimum temperature that should be maintained for mesophilic conditions is 32^{o}C, while the preferred optimum temperature is 35^{o}C (Song *et al*., 2004). When the temperature of the anaerobic digester falls below 32ºC, monitoring of the Volatile Fatty acid (VFA) to alkalinity ratio becomes paramount. The VFA/Alkalinity ratio of 0.3 indicates a stable operation in the AD, while a ratio of 0.3 to 0.4 indicates a potential system operational instability which requires a corrective action (Debik & Coskun, 2009; Song *et al*., 2004). The inhibition of the methane forming bacteria occurs at a VFA/Alkalinity ratio exceeding 0.8 as this results in the accumulation of VFA, which results in acidification of the AD. As such, the rate of methane production and AD is dependent on the digester temperature; thus a suitable temperature lowers the volatile solid concentrations, resulting in biogas production (Geradi, 2003; Song *et al*., 2004).

(b) Alkalinity and pH

Alkalinity plays a critical role for pH control as it serves as a buffer that minimizes rapid changes in pH. As the pH influences enzymatic activity inside the bioreactor, an acceptable pH for methane forming bacteria is between 6.8 to 7.2 (Geradi, 2003; Bouallagui *et al*., 2009). The formation of VFA initially reduces the pH of the AD, with methane forming bacteria consuming VFA, resulting in increased alkalinity and increases in pH, and ultimately the stabilization of the bioreactor (Del Pozo *et al*., 2000). When the anaerobic digester is operating optimally at a pH range of 6.8 to 7.2, the methanogens utilize the VFA to produce biogas (Geradi, 2003; Del Pozo *et al*., 2000). The CO_2 content of the biogas formed has an effect in the pH of the anaerobic system as CO_2 can form carbonic acid, carbonate and bicarbonate alkalinity (Bouallagui *et al*., 2009). The stability of an anaerobic digester is therefore enhanced by high alkalinity concentration within the bioreactor. As such, a decrease in the alkalinity below normal operating conditions can potentially lead to reactor failure (Geradi, 2003; Del Pozo *et al*., 2000).

(c) Retention times

The hydraulic retention time (HRT) and solids retention times (SRT) are two significant quantifiable parameters in the operation of anaerobic digesters (Bolzonella *et al*., 2005). The HRT is the time that wastewater spend inside the anaerobic digester, while the SRT is the average time bacteria spend inside the anaerobic digester. High SRT values are advantageous for anaerobic digestion processes as they maximize removal capacity, reduce the required volume of the digester and provide buffering capacity against the effects of shock loading and toxic compound accumulation from the wastewater supplied to the AD (Geradi, 2003; Manu & Chaudhari, 2003). Furthermore, high SRT values can permit biological acclimation periods to reduce pollutant input to the AD biomass (Bolzonella *et al*., 2005). Similarly, the HRT is rate-limiting during the conversion of volatile solids to gaseous by-products in an AD (Geradi, 2003; Bolzonella *et al*., 2005).

(d) Organic loading rates

The organic loading rate (OLR) is also an important parameter during the anaerobic digestion process as it indicates the quantity of volatile solids and organic matter fed into the AD reactor (Babaee & Shayegan, 2011). The volatile solids are divided into organic solid materials that are biodegradable and fixed solid materials that are non-biodegradable. The loading rate is dependent on the type of wastewater fed into the bioreactor as wastewater used influences biomass biochemical activity occurring in the bioreactor operated under suitable conditions (Babaee & Shayegan, 2011). The degree of microorganism starvation inside the bioreactor is dependent on OLRs: high OLRs are associated with rapid microbial growth rates, although microbial intoxication might occur due high toxicant loading, while at low OLRs, microbial starvation may occur (Gomez, 2011).

2.7.3 Up-flow configured anaerobic digesters: UASB and EGSB

Anaerobic treatment technology such as UASB and EGSB are the frequently used up-flow reactors to degrade organic pollutants in industrial wastewater (Karnchanawon, 2009). The UASB reactor was developed in the late 1970s by Lettinga and his colleagues (Lim, 2009). In the first UASB reactor, successfully applied as a pilot system for a beet sugar refinery in the Netherlands (Lim, 2009; Lettinga, 1980), the feed was introduced at the bottom of the reactor and the product was collected at the top through a three-phase gas-liquid–solids separator (GLSS). The purpose of the GLSS was to allow the collection of biogas from the effluent while retaining solids (biomass) inside of the bioreactor and discharging treated effluent (Henze *et al*., 2008; de Lemos, 2007). For optimal separation, the GLSS needed to be well-designed to separate the biogas and solids from the effluent to avoid biomass washout from the bioreactor, phenomena which has the potential to reduce the performance of the bioreactor (Henze *et al*., 2008). Solids washout occurs as a result of high rates of biogas production, which has a potential to cause granule flotation culminating in solids discharge with the effluent. Such reactors operate at up-flow velocities in the ranges 0.5 to 1.0 m/hr with the height to depth ratio of 0.2 and 0.5 (Lim, 2009). The design is highlighted in Figure 2.3.

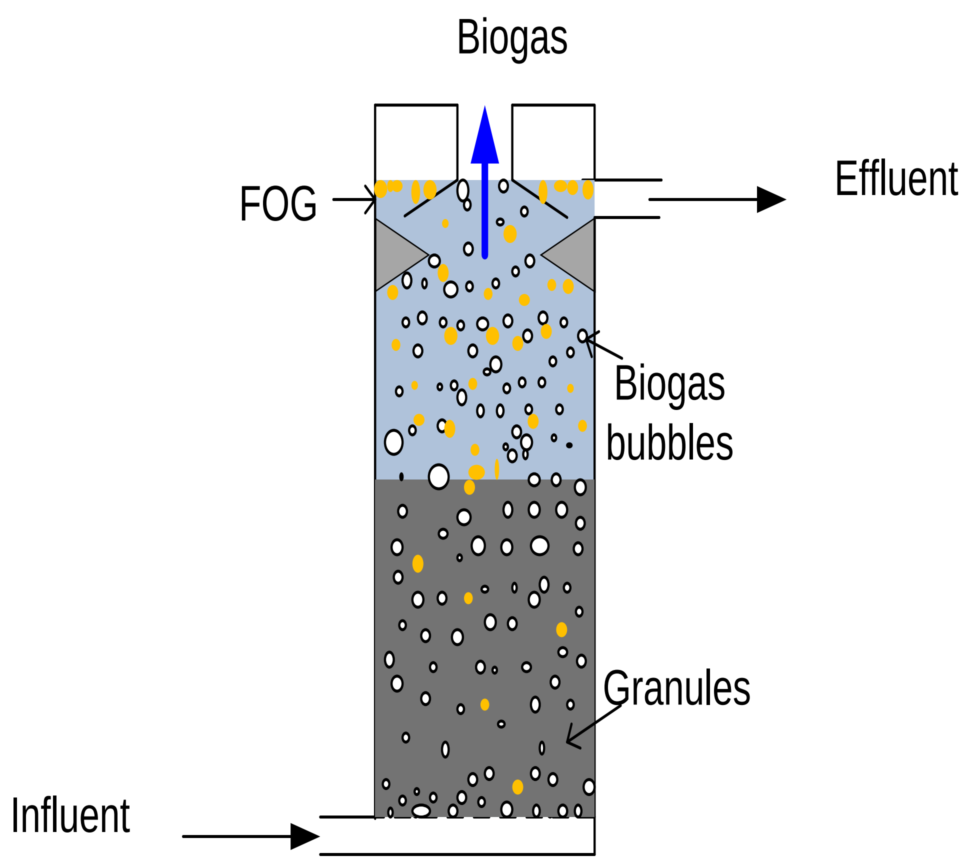

Figure 2.3: The up flow anaerobic sludge bed reactor (UASB) (Karnchanawon, 2009)

The EGSB reactor system is a variant of the UASB-AD concept, with the most distinguishing feature being the use of a high up-flow velocity (typical maintained higher than 6 m/hr) applied with an effluent recycling stream resulting in sludge-bed expansion throughout the bioreactor height (Karnchanawon, 2009). When treating FOG-laden wastewater, biomass flotation due to gas buoyancy effects provided for by FOG can culminate in biomass washout. The height-to-width ratio of the EGSB (Figure 2.4) is 4 to 5, enabling elongated contact between the wastewater and the sludge granules (Lim, 2009).

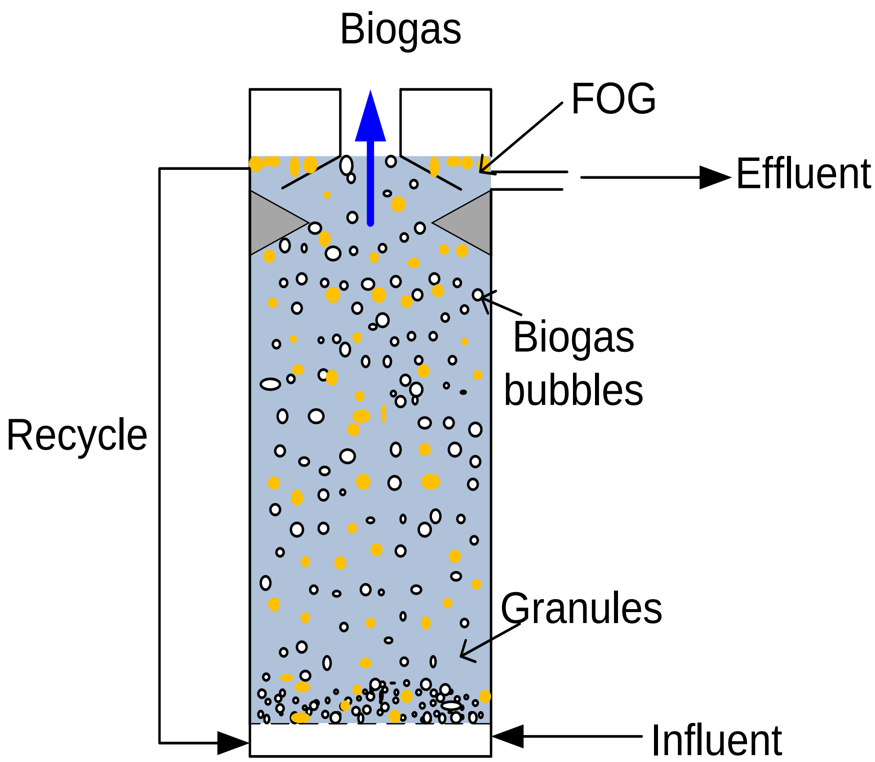

Figure 2.4: The expanded granular sludge bed (EGSB) reactor (Nunez & Martinez, 1999)

2.7.4 Impact of up-flow reactor configuration for the treatment of FOG-laden PSW

Nunez and Martinez (1999) reported 67% tCOD removal rate using an EGSB reactor treating PSW at average OLR of 15 kg COD/m^3.day and HRT of 5 hr. The poor performance of the reactor was reported to be due to periodical sludge washout caused by high FOG loading rates. Sludge washout was also attributed to high OLRs which culminated into a high up-flow velocity, resulting in buoyant forces from pneumatic biogas movement and sludge fluidisation within the EGSB, leading to FOG facilitated flotation, with FOG attached to sludge granules, observable during the operation of the reactor. The continuous sludge washout led to anaerobic system failure because of the decrease in methanogenic activity, a phenomenon requiring periodical system re-inoculation. Miranda (2005) reported that an influent FOG/tCOD ratio above 20% has a detrimental effect on up-flow reactors, resulting in biomass attached to FOG being washed out of the bioreactors. Furthermore, performance improvement of a UASB type reactor was reported to be at a FOG/tCOD ratio of 10% (Miranda, 2005). Del Nery (2007) reported that the success of the up-flow reactor in treating FOG-laden PSW was dependent on an efficient primary treatment system, such as a dissolved air flotation (DAF) system, to reduce FOG and suspended solids prior to the AD system.

2.7.5 Down-flow configured anaerobic digesters: SGBR

The SGBR (Figure 2.5) is a competitive and a practicable high rate AD system for the treatment of industrial and municipal wastewaters. The SGBR reactor was developed by Mach and Ellis (2000) at Iowa State University (USA). The reactor is a simplified down-flow high rate anaerobic granular reactor providing high performance with sustained removal efficiency at low cost due to its operational design and construction simplicity (Mach & Ellis, 2000). The down-flow reactor configuration mode enables a simplified influent flow distribution. Furthermore, it allows for better separation of biogas from granules and wastewater due to its counter-current flow bi-directional operational mode (i.e. against the inlet flow). Additionally, the down-flow mode of operation allows influent solids to be filtered through the granular bed. The reactor utilizes a bed of active anaerobic granules resting on a gravel or mesh wire under-drain for treatment of industrial wastewater with relatively small reactor volumes sizes (Mach & Ellis, 2000). The SGBR reactor reduces high operational costs as packing material, mixing equipment and a recirculation system is not required. However, a declogging system incorporation is advisable for PSW since it contains FOG and high concentrations of suspended solids. Due to its ability to retain high concentration of the biomass within the reactor, the SGBR allows for maximized contact between the active biomass and dissolved organic matter in the wastewater resulting in high organic removal rates (Mach & Ellis, 2000). As such, high OLRs can be used when using SGBR.

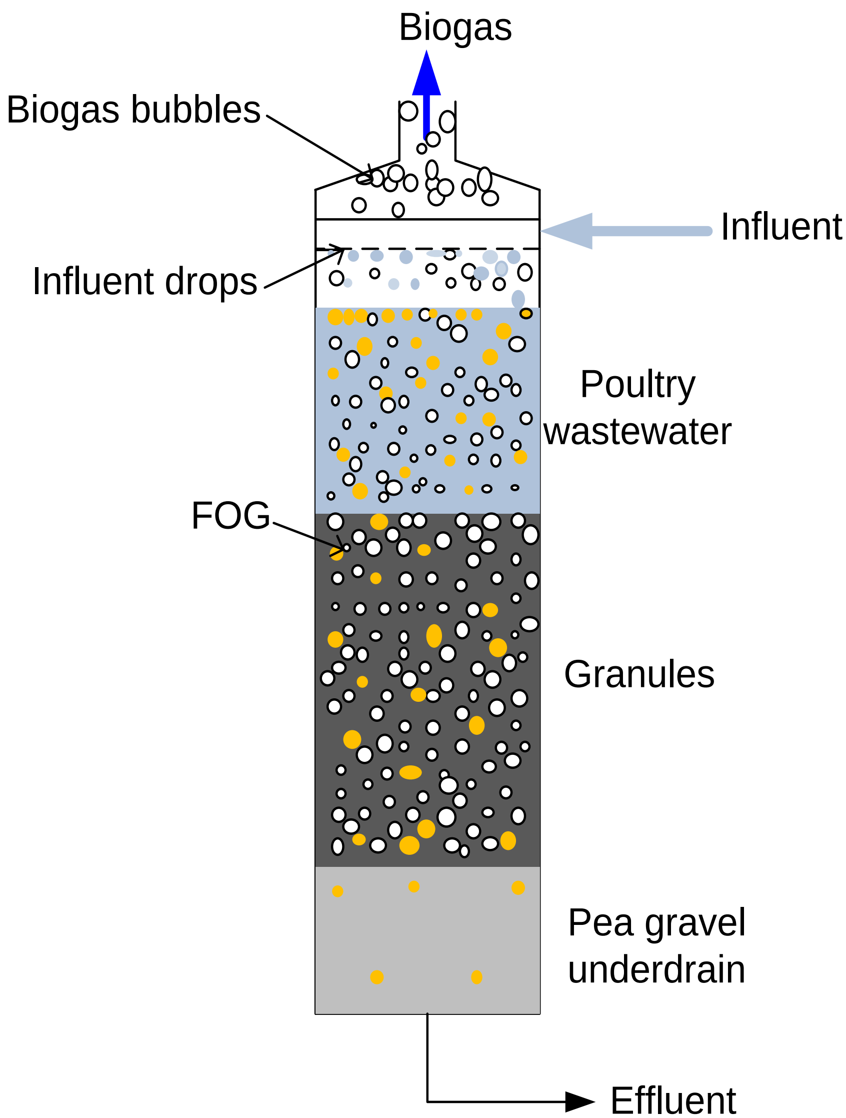

Figure 2.5: The static granular bed reactor (SGBR) (Debik & Coskun, 2009)

2.7.6 Impact of a down-flow reactor configuration for the treatment of FOG-laden PSW

Debik and Coskun (2009) reported that PSW was successfully treated using an anaerobic granule SGBR and consequently compared it with another SGBR containing both anaerobic granular biomass and non-granular biomass. The average tCOD removal efficiencies were reported as greater than 95% for both reactors. The difficulty encountered by upward reactors regarding FOG presence was overcome due to reactor counter-flow direction between the generated biogas and the influent, as minimal quantities of granules were observed washing out of the reactor. Due to pneumatic forces facilitated by biogas generation, FOG attachment to the granules that largely facilitate flotation of less dense materials to the top of reactor is minimized. However, this design does not have an exit port at the top of the reactor for both granules and FOG; thus they remain in the reactor as organic matter for digestion. Oh (2012) reported tCOD removal efficiencies of 94% and 95% for treating meat slaughterhouse wastewater at organic loading rates ranging from 1.01 to 3.56 gCOD/L.day and 0.94 to 12.76 gCOD/L.day, respectively, using an SGBR reactor. The higher rate of tCOD removal using the SGBR reactor compared to that of the EGSB was largely attributed to biomass retention within the reactor.

Some disadvantages were reported by Debik and Coskun (2009) with regard to the efficiency of PSW treatment using an SGBR, highlighting the accumulation of suspended solids at the bottom of reactor resulting in clogging of the underdrain systems due to reduced porosity of the pea gravel in the reactor which suggested that high solids concentrations, particularly constituents of FOG in the influent, can reduce the operability of the system. This leads to reactor redundancies. While periodically applying a backwash with solids withdrawn from the reactor can result in improved system performance, such an operational strategy can mean additional costs and variation in the quality characteristics of the treated effluent.

2.7.7 Performance limitations of the SGBR

The first SGBR reactor, operated over a period of four years, examined the SGBR inadequacies, performance and transition phases within the system (Evans, 2004). The research operation was concluded once performance decreased, as evidenced by low COD removal rate, low biogas production or high solids concentration in the effluent. The transition phase, implemented by varying HRT and OLRs, was monitored to determine if system failure was due to excessive OLRs or as a result of high influent flow rates into the bioreactor. The SGBR reactor reportedly adapted well to new conditions with a period of 24 hrs. The primary physical limitations observed for the SGBR included periodic clogging of the under-drain system, easily resolved by backwashing the effluent to re-fluidise the sludge bed and to collect the flocculated suspended solids through a backwashing port of the bioreactor at the top of the reactor (Evans, 2004).

2.8 Summary

The AD process is a practical and useful treatment technology for FOG-laden PSW. Although this process has numerous advantages, it is important to select an appropriate reactor configuration to achieve maximum reactor performance at lower cost. The reactor performance in treating such FOG laden PSW is influenced primarily by reactor configuration (i.e. up-flow vs down-flow configuration). The up-flow reactor configurations such as UASB, including the EGSB, are largely dependent on the up-flow velocity which often results in periodical sludge washout during high FOG and TSS loading periods. This exacerbates inadequate reactor performance in comparison to the down-flow reactors such as the SGBR, which achieve higher organic load removal efficiency, particularly due to their ability to retain sludge granules and solidified residue within the reactor, although periodic backwashing is required. The aim of this review was to highlight reactor configuration deficiencies, including advantages, when the AD treatment method treats FOG-laden PSW, using either up-flow or down-flow configured systems, with the ultimate aim of achieving high reactor performance.

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CHAPTER THREE

LITERATURE REVIEW CONTINUED: SUBSTRATE REMOVAL KINETIC MODELS FOR ANAEROBIC BIORECTOR SYSTEMS

3. SUBSTRATE REMOVAL KINETIC MODELS FOR ANAEROBIC BIORECTOR SYSTEMS

3.1 Introduction

Modelling of microbial processes in anaerobic reactors can be classified into two categories: 1) microbial growth kinetics and 2) bioreactor performance. Microbial growth kinetics are concerned with the mathematical description of the rate of consumption for substrates such as organic matter by microorganisms, while on the other hand the bioreactor performance focuses on the transport and transformation of the substrate through the bioreactor. The microbial growth kinetics can be divided into four phases namely (a) the lag phase, (b) the exponential (log) phase, (c) the stationary phase and (d) the death phase (Figure 3.1) (Bitton, 2005).

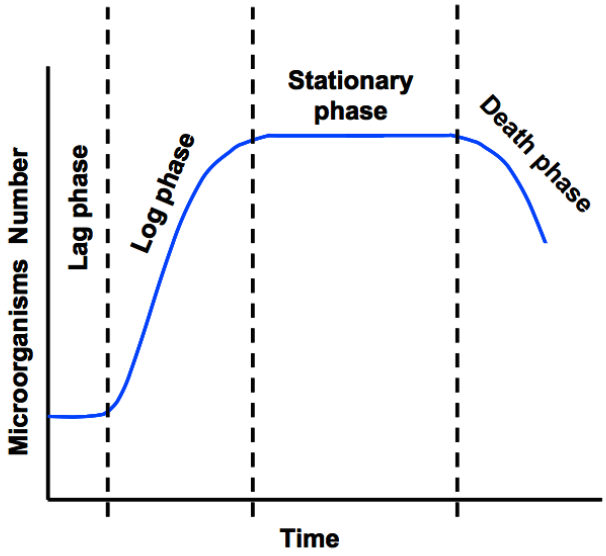

Figure 3.1: Microbial kinetics curve (Bitton, 2005)

The lag phase, also known as the *acclimatisation stage*, is where microorganisms adapt and become accustomed to the wastewater when microorganisms are primarily used to degrade organic matter present in wastewater, which is different from that which they are accustomed (Tortora *et al*., 2004). Biomass age and biodegradability of the organic matter in wastewater affects the duration of the lag phase (Zwietering *et al*., 1990). The exponential phase, also known as the *logarithmic phase*, is indicative of a period when the microorganism population grows exponentially (Kuklinsky- Sobral *et al*., 2004). This exponential growth depends on the type of microbial population and wastewater quality strength; thus biodegradation of the soluble organic matter and a suitable temperature. The steady-state growth phase, also known as the *stationary phase*, occurs when microorganism proliferation is reduced and/or is non-existent and the rate of microbial population growth is equivalent to the rate of microbial population death (Kuklinsky- Sobral *et al*., 2004). This subsequently leads to a *death phase* whereby the death rate is higher than the growth rate, resulting in the disappearance of active microbial population because of the presence of toxicants which effectively reduce microbial metabolic activity, culminating in microbial death, a phenomenon which is also due to lack of nutrients. In certain instances, this results in the microbial population exhibiting predatory behaviour, with some organisms producing secondary metabolites antagonistic against other organisms with a lack of electron acceptors limiting respiration. This chapter reviews kinetic models currently in use for soluble organic matter utilisation rates by heterogeneous microorganisms in an anaerobic digestion process.

3.2 Monod kinetics

The Monod's model, one of the most frequently used kinetic models, is for describing the rate of change of biomass concentration in a reactor, assuming such growth is dependent on a growth limiting substrate (i.e. soluble organic matter); thus its concentration in the wastewater being treated. Since the model describes microbial growth behaviour when utilising a continuous system, microbial growth is dependent on the influent and effluent biomass concentration, including biomass growth and decay in the defined system (Lyberatos, 1999). For a continuous system, an accounting of biomass concentration can be described using Eq. 3.1:

$$\frac{dX}{dt} = \frac{Q}{V}(X_0\text{-}X_E) + (\mu - K_d)X \qquad 3.1$$

Where X = concentration of the microorganism, g VSS/L; V = volume of the reactor, L; Q = flow rate of the influent, L/day; X_0 *and* X_E= concentration of microorganisms in the influent and effluent, g VSS/L; μ = specific growth rate, 1/day; and K_d = endogenous decay coefficient, 1/day

The specific rate of the microbial growth in Eq. 3.1 can then be described using the Monod model, as the Monod model is used to describe the relationship between the specific growth rate of the microorganisms and the concentration of the limiting substrate (i.e organic matter in PSW used in this study) as shown in Eq. 3.2:

$$\mu = \mu_{max}\frac{S_e}{K_S+S_e} \qquad 3.2$$

Where μ_{max} = Maximum specific growth rate, 1/day; K_s = Half velocity (affinity) constant, g/L; and S_e= Effluent substrate concentration, g/L.

Assuming that the influent PSW is free of any anaerobic biomass $(X_0 = 0)$ with the AD driven bioreactor being at steady-state ($\frac{dX}{dt} = 0$), Eq. 3.1 can be simplified into Eq. 3.3:

$$\frac{Q}{V}(X_E) = (\mu - K_d)X \qquad 3.3$$

Making the specific growth rate (μ) of the AD biomass the subject of the formula results in Eq. 3.4:

$$\mu = \frac{QX_E}{VX} + K_d \qquad 3.4$$

Since the solids retention time (SRT), θ_c is a function of V, X, Q, X_E and can be defined as the ratio of the total AD biomass in the reactor (VX) to the AD biomass concentration in the effluent including sloughed-off biomass when applying a backwashing procedure in the AD system (QX_E), as indicated by Eq. 3.5:

$$\theta_c = \frac{VX}{QX_E} \qquad 3.5$$

A new relationship can be deduced by substituting Eq. 3.5 into Eq. 3.4, culminating into a simplified relationship, as in Eq. 3.6:

$$\mu = \frac{1}{\theta_c} + K_d \qquad 3.6$$

Furthermore, equating Eq. 3.6 to Eq. 3.2 results in another relationship as shown in Eq. 3.7:

$$\mu_{max}\frac{S_e}{K_S+S_e} = \frac{1}{\theta_c} + K_d \quad 3.7$$

To predict the organic matter concentration in the effluent from the continuous AD systems, or in other words to quantitatively determine the residual substrate (S_e) , (i.e. COD concentration), Eq. 3.7 can be simplified into Eq. 3.8, which can be used to predict the effluent COD concentration under steady-state environmental conditions.

$$S_e = \frac{K_S\left(K_d+\frac{1}{\theta_C}\right)}{\mu_{max}-K_d-\frac{1}{\theta_c}} \quad 3.8$$

For adequate AD system performance, it is desirable that K_d is minimal, such that Eq. 3.8 become Eq 3.9:

$$S_e = \frac{K_S\left(\frac{1}{\theta_C}\right)}{\mu_{max}-\frac{1}{\theta_C}} \quad 3.9$$

Similarly, Eq. 3.10 can be used to describe the rate of change of soluble organic matter concentration in the continuous system designed.

$$-\frac{dS}{dt} = \frac{Q}{V}S_0-\frac{Q}{V}S_e-\frac{\mu X}{Y} \quad 3.10$$

Where Y is the growth yield coefficient as a quantifiable measure of the biodegradability of the organic matter in the PSW.

Like the AD biomass balance under steady state conditions, considering that the variability of the rate of organic matter in the AD is minimal $\left(\frac{dS}{dt} = 0\right)$, Eq. 3.10 can be simplified by substituting the specific AD biomass growth rate (Eq. 3.6) in Eq. 3.10, with subsequent linearization, culminating in Eq. 3.11:

$$\frac{(S_0-S_e)}{\theta_H X} = \frac{1}{Y}\left(\frac{1}{\theta_c} + K_d\right) = \frac{1}{Y}\frac{1}{\theta_C} + \frac{K_d}{Y} \quad 3.11$$

Where $\frac{Q}{v} = \frac{1}{\theta_H}$ with θ_H being the HRT.

Using the linearized form of Eq. 3.11, both the slope and the intercept $\frac{1}{Y}$ and $\frac{K_d}{Y}$ can retrospectively be quantified. Rearranging Eq. 3.7 using the maximum specific growth rate of AD biomass as an output results in Eq. 3.13 whereby the value of the maximum specific growth rate (μ_{max}) and the endogenous decay coefficient (K_d) can be determined.

$$\frac{\theta_c}{1+\theta_c K_d} = \frac{K_s}{\mu_{max}} \frac{1}{S_e} + \frac{1}{\mu_{max}} \qquad 3.12$$

Furthermore, since the PSW contains an average of ~17% of soluble organic matter, assumed to be biodegradable, it is expected that k_d will be minimal, particularly when the AD system is operating optimally under steady state conditions. Thus, Eq. 3.11 can be transformed into Eq. 3.13:

$$\theta_c = \frac{K_s}{\mu_{max}} \frac{1}{S_e} + \frac{1}{\mu_{max}} \qquad 3.13$$

3.2 Modified Stover-Kincannon model

The Stover-Kincannon model is one of several models that have been used to describe the overall kinetics of substrate removal rates from biological reactors. The model assumes a steady-state relationship for the substrate removal rate, as indicated in Eq. 3.14 (Abtahi *et al*., 2013):

$$-\frac{dS}{dt} = \frac{Q}{V}(S_0 - Se) \qquad 3.14$$

Where $-\frac{dS}{dt}$, represents substrate removal rate; while S_0 and S_e are the influent and effluent substrate concentrations (g COD/L), respectively; and *Q* is the influent and effluent flow rate (L/day) assumed to be equivalent under steady-state conditions; while *V* is the working volume and/or the reactor (*L*) capacity. The periodical change of the digestible substrate can be represented using a simple modification of the Stover-Kincannon model, as in Eq. 3.15, proposed for rotating biological contactor (RBC) systems as follows:

$$-\frac{dS}{dt} = \frac{U_{max}(\frac{QS_0}{V})}{K_B+(\frac{QS_0}{V})} = \frac{U_{max}(\frac{S_0}{\theta_H})}{K_B+(\frac{S_0}{\theta_H})} \quad 3.15$$

Where U_{max} is the maximum substrate removal rate constant (g/L.day); and K_B is the Stover-Kincannon saturation constant (g/L.day).

The original Stover-Kincannon model can be described by Eq. 3.16 (Kincannon & Stover, 1982):

$$\frac{dS}{dt} = \frac{U_{max}(\frac{QS_0}{A})}{K_B+(\frac{QS_0}{A})} \quad 3.16$$

Whereby the disc surface area (A) in RBCs represented the relationship of the total active and disc biomass concentration for RBC systems. The model assumed that suspended biomass in the aqueous phase of the RBCs is negligible when compared to the disc attached active biomass (Kincannon & Stover, 1982). The simple modification of the model based on the volume of the anaerobic filter, thus the sludge bed (*V*) instead of the surface area (*A*) of the disc used.

The introduction of the concept of the total organic loading rate $\left(\frac{Q_0}{V}\right)$ to the Stover-Kincannon model differentiates the model from the Monod's model. Kincannon and Stover (1982) claimed that the efficiency and substrate removal rates exhibited a definitive relationship between both the hydraulic loading rates (HLT) and organic loading concentration (OLC), defined as HRTs and n this research. Furthermore, research results by Kincannon and Stover (1982) indicated that the removal of the substrate, and thus the efficiency of the system used, is dependent on the quantity of total organics applied to the biological reactors rather than the organic loading rate OLRs. This meant that the quantity of the organic substrate removed by the bioreactor system is equivalent to the loading rate regardless of whether loading is achieved by low HLR at a high concentration or high HLR at low organic concentration (Kincannon & Stover, 1982). By linearizing Eq. 3.16 in terms of the inverse of the loading removal rate result in Eq. 3.17, where the $\left(\frac{dS}{dt}\right)^{-1} = \frac{\theta_H}{(S_0\text{-}S_e)}$,

$$\left(-\frac{dS}{dt}\right)^{-1} = \frac{\theta_H}{(S_0\text{-}S_e)} = \frac{K_B}{U_{max}}\left(\frac{\theta_H}{S_0}\right) + \frac{1}{U_{max}} \quad 3.17$$

A graphical illustration of the inversed loading removal rate $\left(\frac{\theta_H}{S_0\text{-}S_e}\right)$ against the inverse of the total loading rates $\left(\frac{\theta_H}{S_0}\right)$ culminates in a straight-line of which the slope $\left(\frac{K_B}{U_{max}}\right)$ and the intercept $\left(\frac{1}{U_{max}}\right)$ can be determined. From such a correlation, the U_{max} and K_B values can be estimated and used to determine the effluent substrate concentration for a given bioreactor capacity: volume and influent concentration. Considering the volume of the sludge bed, the concentration of the substrate into the bioreactor will be equivalent to the concentration of the substrate out of the bioreactor including the concentration of the substrate which is biodegradable in a volume of the wastewater. Therefore, Eq. 3.18 can be used to describe the substrate balance in and out of the volume of the AD bioreactor:

$$QS_0 = QS_e + V\left(\frac{ds}{dt}\right) \quad 3.18$$

Substituting the Eq. 3.17 into Eq. 3.18 for the relationship of $\left(\frac{\boldsymbol{ds}}{\boldsymbol{dt}}\right)$ will result in Eq. 3.19 as follows:

$$QS_0 = QS_e + V\left(\frac{U_{max}(S_0/\theta_H)}{K_B+(S_0/\theta_H)}\right) \quad 3.19$$

For simplification, Eq. 3.19 can be solved using either the required reactor capacity (*V*) (i.e. anaerobic digester bed) or the residual substrate concentration in the effluent (COD in the exit port/stream of the designed system) as indicated in both Eq. 3.20 and 3.21, respectively.

$$V = \frac{QS_0}{(U_{max}S_0/\,S_0\text{-}S_e)\text{-}K_B} \quad 3.20$$

$$S_e = S_0\text{-}\frac{U_{max}S_0}{K_B+\left(\frac{S_0}{\theta_H}\right)} \quad 3.21$$

3.4 Grau-second-order model

The Grau second-order kinetic model, which describes substrate removal rates, is shown in Eq 3.20 (Grau, 1975):

$$-\frac{ds}{dt} = k_s X \left(\frac{S_e}{S_0}\right)^2 \qquad 3.22$$

Where k_s can be defined as the Grau substrate removal rate constant $(1/d)$, X is the average AD biomass concentration in the bioreactor (g VSS/L); with S_0 and S_e being both the influent and effluent substrate concentration (gCOD/L), respectively; with $t = \theta_H$, being equivalent to HRT. Eq. 3.22 can be integrated and linearized to the format shown in Eq. 3.23:

$$\frac{\theta_H S_0}{S_0 - S} = b\theta_H + \frac{S_0}{k_s X} \qquad 3.23$$

With the coefficient b in Eq. 3.23 being close to unity, reflecting on the uniqueness to attain complete COD reduction in the wastewater being treated. A further simplification of Eq. 3.23 can be achieved by replacing the substrate removal efficiency fraction $\left(\frac{S_0 - S_e}{S_o}\right)$ with the symbol E and substrate kinetics$\left(\frac{S_0}{k_s X}\right)$ with the symbol a, resulting in Eq. 3.24:

$$\frac{\theta_H}{E} = b\theta_H + a \qquad 3.24$$

Similar to the Stover and Kincannon linearization technique to quantitatively determine the kinetic parameters in a linearized form, E.q 3.24 can illustratively be demonstrated by graphically comparing $\frac{\theta_H}{E}$ against θ_H, to determine kinetic parameters, a and b, which can be calculated from the intercept and slope of the linearized model. The estimation of a and b can be used to predict residual substrate concentration (S_e) from the AD system using Eq. 3.25:

$$S_e = S_0 \left(1 - \frac{\theta_H}{a + b\theta_H}\right) \qquad 3.25$$

3.5 Summary

This section of the thesis presented a review of kinetics models for substrate removal in an AD reactor used in this study. The models described and motivated for in this chapter were utilized in Chapter Six for modelling of the COD removal rates using a Static Granular Bed reactor (SGBR) treating poultry slaughterhouse wastewater, a system determined to perform better (Chapter Five) in comparison to an EGSB (Chapter Four).

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CHAPTER FOUR

RESULTS

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Supplementary data is provided in the Appendix A

NB: See Appendix C for improved operation strategy of the EGSB reactor

4. PERFORMANCE OF AN EXPANDED GRANULAR SLUDGE BED (EGSB) REACTOR COUPLED WITH ANOXIC AND AEROBIC BIOREACTORS FOR TREATING POULTRY SLAUGHTERHOUSE WASTEWATER

4.1 Introduction

The generation of wastewater from slaughterhouses has progressed into an environmental concern concomitant with the growth of the poultry industry, as demand for poultry products has increased (Debik, 2009). Poultry slaughterhouses consume significant quantities of fresh water while slaughtering and cleaning of surfaces, generating of a significant quantity of high strength wastewater (Debik, 2009), containing high organic matter, with high nitrogen and phosphorus constituents (Avula *et al*., 2009). The high phosphorous concentration comes from blood, cleaning and sanitizing agents, with the phosphorous in the form of organic or inorganic phosphates (Arvanitoyannis *et al*., 2008; Avula *et al*., 2009). Furthermore, slaughterhouse wastewater contains a high quantity of biodegradable organic matter with a BOD_5 range of 1.2 to 2.6 g/L, with the soluble fraction of the BOD_5 ranging between 40 to 60% (De Nardi *et al*., 2008; De Nardi *et al*., 2011). The primary pollutants contributing to the BOD_5 in poultry slaughterhouse wastewater are insoluble proteins from carcass debris, blood, fats and non-biodegradable matter from feathers (Manjunath *et al*., 2000; Avula *et al*., 2009; Yordanov, 2010). The wastewater contains predominantly 35% more protein, resulting in much higher BOD_5 and tCOD as compared to municipal sewerage (Zhang *et al*., 2008; Avula *et al*., 2009). Clearly, then, poultry slaughterhouse wastewater must be treated efficiently *prior* to disposal into the receiving freshwater sources as a means to prohibiting environmental pollution (Debik & Coskun, 2009).

Biological anaerobic treatment technology is one of the most highly recommended treatment methods worldwide in the treatment of wastewater from the food industry due to its technological ability to treat high strength wastewater (Karnchanawong *et al*., 2009). Numerous research studies have highlighted the application of a biological anaerobic digester for the treatment of poultry slaughterhouse wastewater (Avula *et al*., 2009). The feasibility of using a multi-stage process with an Expanded Granular Sludge Bed (EGSB) anaerobic digester coupled with anoxic and aerobic reactors was examined in this part of the study.

Anaerobic digestion has been used in treating poultry slaughterhouse wastewater as it can efficiently handle variations in particulate matter and FOG loading rates. Anaerobic bioreactors, such as the up-flow anaerobic sludge bed (UASB) reactors, have been used successfully to treat poultry slaughterhouse wastewater. In fact, Del Nery *et al*. (2007) obtained treatment efficiency rates of 65% for total tCOD and 85% for soluble tCOD reduction at an average organic loading rate (OLR) of 1.64 kg COD/m^3.day using a full scale UASB reactor. Similarly, Debik *et al*. (2009) used a Static Granular Reactor Bed (SGBR) to treat the poultry slaughterhouse wastewater, achieving average tCOD removal rates of 95%. Similarly, the EGSB, well-known to increase sludge expansion for improved efficiency due to its recirculation stream, reportedly achieved tCOD removal of 67% by Nunez (2009) in treating poultry slaughterhouse wastewater without a pre-treatment process.

In this part of the study, a two-stage process containing an EGSB anaerobic digester coupled with anoxic and aerobic bioreactors was proposed to treat poultry slaughterhouse wastewater from a poultry product manufacturer in South Africa. From a South African perspective, the use of such a system has not been applied on an industrial scale, particularly for the treatment of poultry slaughterhouse wastewater. Therefore, this study was conducted to assess the performance of the bench-scale EGSB anaerobic bioreactor coupled with anoxic and aerobic bioreactors in treating the poultry slaughterhouse wastewater, particularly in terms of meeting the municipal discharge standards of South Africa.

4.2 Objectives

The objectives of this part of the study were as follows:

- to evaluate the effectiveness of the up-flow EGSB reactor coupled with anoxic-aerobic tank configuration in treating poultry slaughterhouse wastewater;
- to investigate the need, if any, of a pre-treatment stage prior the anaerobic digestion stage for improving the performance of the reactor in both EGSB; and
- to identify limitations of the EGSB reactor configurations for the treatment of poultry slaughterhouse wastewater.

4.3 Materials and methods

4.3.1 Experimental set-up and equipment

The laboratory bench-scale system was operated in a two-stage process consisting of an Expanded Granular Sludge Bed (EGSB) reactor followed by the anoxic and aerobic bioreactors (see Figure 4.1). The system was operated over a period of 26 days.

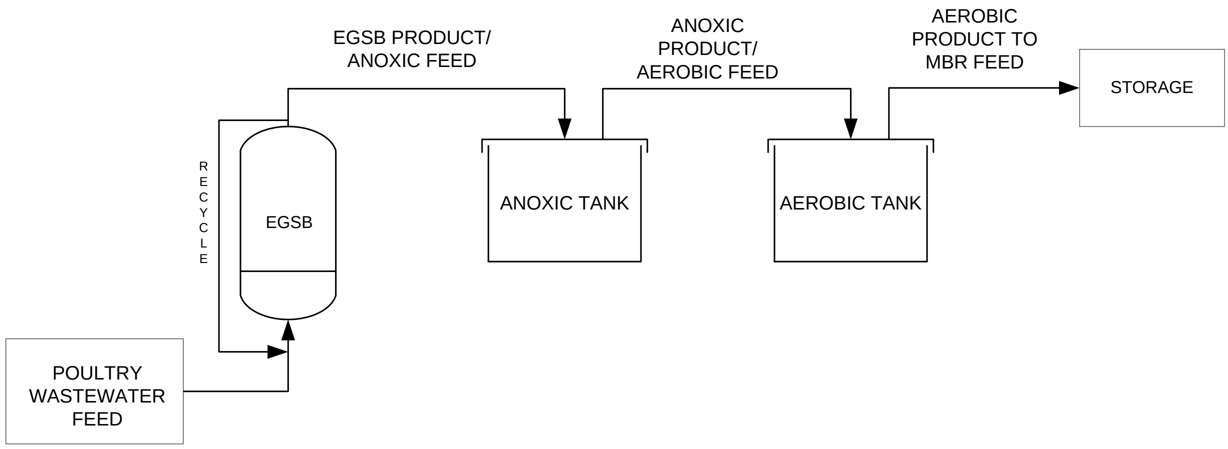

Figure 4.1: Schematic diagram for the laboratory bench-scale EGSB, anoxic and aerobic bioreactor system

4.3.2 The EGSB laboratory bench-scale reactor set-up

The purpose of the EGSB reactor was to effectively reduce the organic load of the feed after the effluent was treated in the anoxic and aerobic bioreactors. SB consisted of a cylindrical-shaped vessel with a total working volume of 1.2 L with a height and inner diameter of 0.22 and 0.06 m, respectively. The reactor consisted of a gas-liquid-solid separator at the top of the column for the separation of solids and biogas from the liquid phase. The biogas produced from the EGSB reactor was collected at the top of the reactor using Tedlar bags. The influent was pumped continuously and fed from the bottom of the reactor using a Gilson (Germany) peristaltic pump, with effluent withdrawn from the top at the same rate. The effluent liquid phase was split into two streams: 1) EGSB product and 2) the recirculation stream. The recirculation stream from the top was mixed with the fresh effluent feed to the EGSB reactor. The liquid up-flow velocity was maintained at 1.1 m/hr. The reactor operated at a constant temperature of 37°C, regulated using a water jacket through which water from a thermostatic water bath circulated. The reactor was also insulated to prevent heat loss to the environment.

4.3.3 The anoxic and aerobic bioreactor set-up

The purpose of the anoxic tank and aerobic systems was for denitrification and nitrification processes, respectively. The anoxic and aerobic systems had a working volume of 0.825 L each. The anoxic tank was placed on a magnetic stirring plate for continuous homogenization of the contents. The aerobic tank had two miniature air-diffusers with air supplied at a flow rate of 1.9 L/min.

4.3.4 Slaughterhouse wastewater collection and storage

The poultry slaughterhouse wastewater was collected from a slaughterhouse located in the Western Cape of South Africa. The characteristics of the wastewater are summarized in Table 4.1, presenting average values of parameters quantified over a 3-week sampling period. All measurements were performed according to standard methods (APHA, 2005).

Table 4.1: Characteristics of the wastewater from industrial slaughterhouse in the Western Cape, South Africa

Parameter	Unit	Poultry slaughterhouse waste water	
		Range	Average
pH	-	6.5-8.0	6.88
Alkalinity	mg/L	0- 489	489
tCOD	mg/L	2133-4137	2903
sCOD	mg/L	595-1526	972
BOD_5	mg/L	1100-2750	1667
TKN	mg/L	77-352	211
Ammonia	mg/L	29-51	40
TP	mg/L	8 -27	17
FOG	mg/L	131-684	406
TDS	mg/L	372-936	654
TSS	mg/L	315-1273	794
VSS	mg/L	275-1200	738
Soluble proteins	mg/L	0-368	72
VFA	mg/L	96-235	235
Nitrates	mg/L	0-2903	2903

4.3.5 Seed preparation

The inoculum used for the EGSB was prepared as a mixture of 0.3 L granular sludge taken from a full-scale up-flow anaerobic-sludge bed (UASB) reactor treating brewery effluent (SAB Miller, Newlands Brewery, South Africa) and 0.1 L of digested sewage sludge taken from a municipal wastewater treatment plant (City of Cape Town, SA). The anoxic and aerobic bioreactors were inoculated with 0.0825 L of digested sewage sludge and 0.7425 L of poultry slaughterhouse wastewater.

4.3.6 EGSB operating conditions

During the start-up phase, the laboratory bench-scale EGSB was operated at an HRT of 7 days (168 hr) and an OLR of 0.5 g COD/L.day. Thereafter, the HRT was decreased each week to 4 days (96 hr), and subsequently to 3 days (72 hr), with OLRs being increased to 0.7 and 1.0 g COD/L.day, respectively.

4.3.7 Analyses of poultry slaughterhouse industrial wastewater

Twenty-five (25) litres of fresh poultry slaughterhouse effluent were received every week and analysed for pH, TDS, BOD_5, tCOD, NH_4^+, TSS, TP, FOG and NO_3^-. A sample was also sent to an independent accredited laboratory (Scientific services, City of Cape Town, SA) for full chemical analysis, for comparative analyses.

4.3.8 Combined EGSB-anoxic-aerobic system operational scheme and monitoring

Analyses of the EGSB feed, EGSB product, anoxic and aerobic bioreactors product streams were monitored to assess the performance of the entire system, with values of parameters such as the chemical oxygen demand (tCOD), pH, analysed every 48 hrs.

4.4 Results and discussion

The system was started at an HRT of 7 days (168 hr) and OLR of 0.5 g COD/L.day to maintain start-up operating conditions, providing the necessary acclimatization time for biomass and system stability. During the first week of operation, the EGSB experienced sludge washout due to high FOG and suspended solids loading from the feed. The sludge washout inhibited the EGSB performance. The following sub-sections describe and discuss the results obtained in the study.

4.4.1 Variation of OLR and HRT on the EGSB reactor salinity tolerance test

The EGSB-anoxic-aerobic system was continuously operated for a period of 26 days at different HRTs and OLRs. The HRT of the EGSB was maintained at 7 days (168 hr) during the start-up period and maintained at this rate for a period of one week. The HRT was thereafter decreased step-wise to 4 days (96 hr), then further reduced to 3 days (72 hr), respectively (Figure 4.2). Figure 4.2 also showed variation of the OLR, ranging from 0.2 to 2.2 g COD/L.day. The up-flow velocity in the EGSB was kept constant at 1.1 m/hr. The tCOD in the feed ranged between 2133 to 4137 mg/L with an averaged tCOD of 2903 mg/L. The tCOD was used in this study as a comparative parameter to quantify system performance and to monitor the effect of the OLR throughout the study.

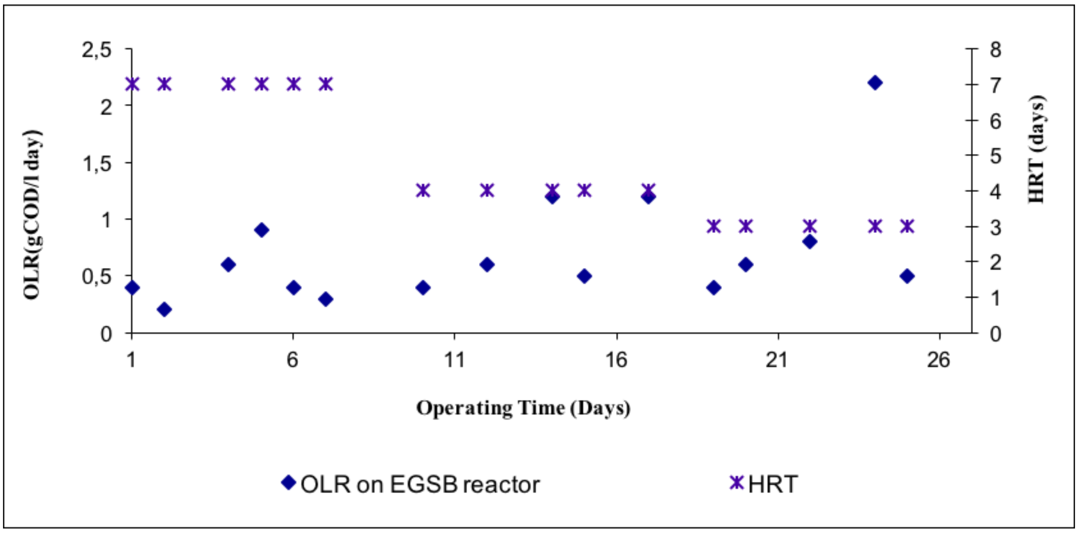

Figure 4.2: Variation of OLR and HRT during experimental studies

4.4.2 EGSB performance and COD removal

The average tCOD removal was observed to be 40%, 57% and 55% at phase 1, phase 2 and phase 3 respectively, as shown in Figure 4.3. The average tCOD removal in the EGSB was found to be 51%. It was observed that the tCOD percentage removal decreases at the highest OLR (phase 3) of 1.0 g COD/L.day, attributable to the high feed flow rate to the EGSB, and the high FOG loading present in the feed, including the overall residence time of the poultry wastewater, within the EGSB. Furthermore, FOG generally increases sludge washout, which lowers reactor efficiency, particularly for any anaerobic reactor. A study conducted by Miranda *et al*. (2005) found that an influent FOG/COD ratio above 20% has a detrimental effect on a full-scale UASB reactor, resulting in biomass washout and therefore system failure. The performance of the UASB reactor was reported to have improved at an FOG/COD ratio of 10%.

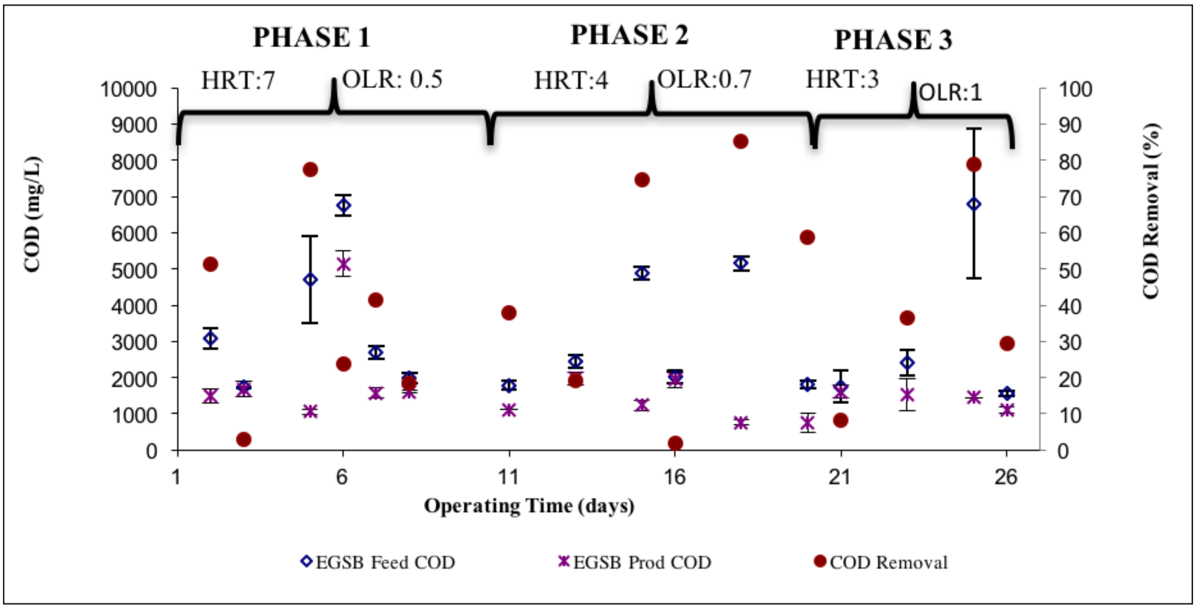

Figure 4.3: Variation of tCOD concentration at different OLRs and HRTs and tCOD removal efficiency on the EGSB reactor

4.4.3 Overall COD removal of the EGSB, anoxic and aerobic bioreactor

Figure 4.4 illustrates the overall tCOD removal efficiency of the system determined from the inlet effluent (i.e. EGSB feed) and the final exit effluent from the aerobic tank. The overall average tCOD removal of the system was 65%. As indicated in Figure 4.3 and 4.4, the data shows 63% tCOD removal as its highest during the second operating phase. The average overall tCOD efficiencies for phase 1 and phase 3 were 52% and 53%, respectively. The low tCOD removal was due to periodical sludge washout on the anaerobic digester or pipe blockages due to accumulation of FOG in the feed line resulting in reduced feed flow rate. Furthermore, reduced anaerobic feed flow rate can result in the secondary system washout (anoxic and aerobic bioreactors) because of lower flow rate out of the EGSB. This led to the re-inoculation of the secondary system, thereby reducing the overall efficiency of the system.

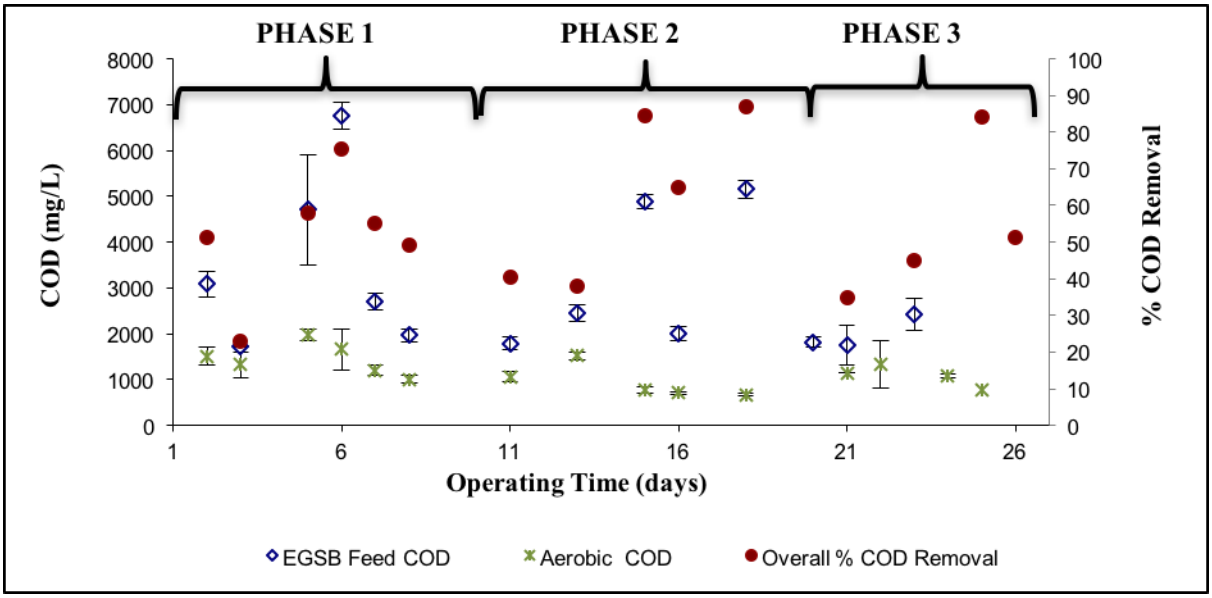

Figure 4.4: Variations of tCOD concentration at different OLRs, HRTs and tCOD removal efficiency

4.4.4 Variation in pH

The pH was used to monitor the stability of the EGSB reactor and anoxic and aerobic bioreactors, as depicted in Figure 4.5. The EGSB feed and EGSB product was stable at a range of 6.5 to 8 throughout the study, the optimal condition for methanogens activity. The pH of anoxic and aerobic tank was at a range 5 to 8. The results also indicate a pH drop below 6 for the EGSB feed, anoxic and aerobic tank between day 17 and 23 of operation.

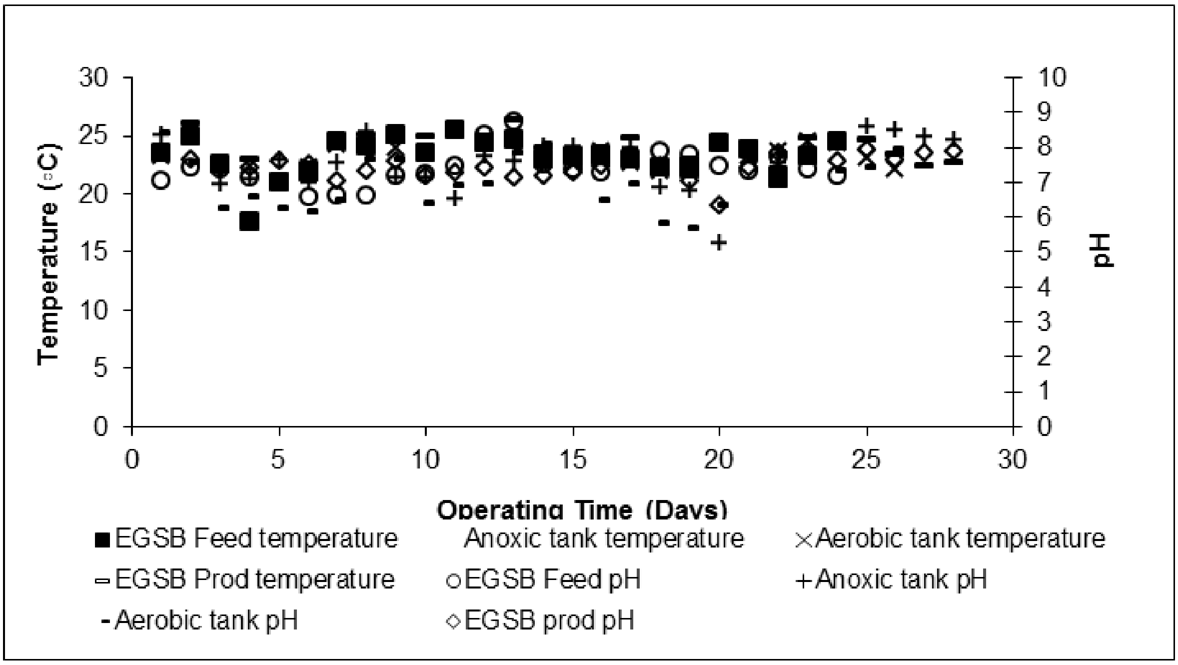

Figure 4.5: Variation of pH during operation

4.5 Summary

Generally, slaughterhouses consume a large quantity of fresh water and thus generate large quantities of high strength wastewater. While this can be treated successfully using low cost biological treatment processes, in this study, the feasibility of using an EGSB anaerobic reactor coupled with anoxic and aerobic bioreactors for the treatment of poultry slaughterhouse wastewater was investigated. The poultry slaughterhouse wastewater was characterized by high chemical oxygen demand (tCOD), 2 to 6 g/L, with an average biological oxygen demand (BOD_5) of 2.4 g/L and average FOG being 0.55 g/L. A continuous EGSB anaerobic reactor was operated for 26 days at different hydraulic retention times (HRT) – 7 (168 hr), 4 (96 hr), 3 (72 hr) days – and organic loading rates (OLR) of 0.5, 0.7 and 1.0 g COD/L.day, respectively, to assess the bioremediation of the poultry slaughterhouse wastewater. The average tCOD removal from the EGSB was 40%, 57% and 55% at the different OLRs and HRTs assessed. At a high OLR of 1.0 g COD/L.day, the overall tCOD removal from the system (EGSB-anoxic/aerobic) averaged 65%. The system experienced periodical sludge washout during high FOG and suspended solids loading. It was concluded that the EGSB system requires a dissolved air flotation (DAF) or a skimmer pre-treatment system for FOG/suspended solid reduction, as the performance of the overall system was observed to deteriorate over time due to the presence of a high quantity of FOG including suspended solids. See Appendix C for results obtained during a EGSB re-run based on improved operation strategy. Furthermore, due to poor performance of the up-flow EGSB reactor, the down-flow SGBR was also proposed in Chapter Five as a possible alternative to treat PSW coupled with the ultra-filtration membrane.

Acknowledgement

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CHAPTER FIVE

RESULTS

This chapter was published as:

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Supplementary data as provided in Appendix B

5. TREATMENT OF POULTRY SLAUGHTERHOUSE WASTEWATER USING A STATIC GRANULAR BED REACTOR (SGBR) COUPLED WITH ULTRAFILTRATION (UF) MEMBRANE SYSTEM

5.1 Introduction

Due to an increased demand of poultry products, the poultry industry in South Africa (SA) has grown exponentially in recent years with more than 470 slaughterhouses (Department of Agriculture and Rural Development, 2009). The poultry product annual consumption in SA exceeds the combined consumption of all other animal protein sources. Furthermore, 65.5% of locally produced animal protein consumed on a volume basis is supplied by the poultry industry (The South African Poultry Industry Profile, 2012). The use of potable water for the processing of poultry products ensures that a hygienically safe product is available to consumers (Department of Agriculture and Rural Development, 2009). However, due to the increasingly stringent governmental regulations, increasing treatment costs, imminent water scarcity and environmentally conscious consumers, the treatment of wastewater has become a major concern in the general meat processing industry and specifically in the poultry industry (Kobya *et al.*, 2005; Park, 2009).

Poultry slaughterhouse water consumption varies according to the type of process employed, equipment used, productivity including capacity of the processing facility, and the wastewater management practices (Molapo, 2009). Poultry slaughterhouses consume a considerable quantity of water for cleaning, rinsing of carcasses and poultry products. Furthermore, fresh water is used for sanitizing, disinfecting slaughterhouse facilities and equipment (Department of Agriculture and Rural Development, 2009; Plumber, 2009; Avula *et al.*, 2008). SA poultry slaughterhouses use approximately 15 to 20 litres of water per bird processed (CSIR, 2010). A summary of the water consumption for a typical poultry slaughterhouse in SA is shown in Table 5.1.

Table 5-1: Water consumption in a typical South African poultry slaughterhouse (Molapo, 2009)

Area	Operations	Water consumed (%)	Average water consumed (%)
	Lairages	5 – 12	10
Processing	Slaughter and carcass dressing	12 – 33	20
	Offal handling	11 – 60	25
	Hot water	14 – 36	25
Utilities	Cooling and refrigeration	5 – 11	8
	Steam raising	2 – 9	5
Services	Ablutions, laundry and general washing	1 – 12	7

The composition of this wastewater may differ from one slaughterhouse to another depending on the type of bird, the water consumption per processed bird, as well as the type of process used (Debik & Coskun, 2009; Del Nery *et al.*, 2007). These wastewaters are typically characterized by high concentrations of organic compounds such as BOD_5 and tCOD, including high levels of nitrogen, phosphorous, pathogenic microorganisms, suspended solids, and FOG as a result of blood, faeces, carbohydrates, feathers and proteins (Oh *et al.*, 2014; Yornadov, 2010), as highlighted in Table 5.2. The high content of organic matter can be attributed to the residual blood in the wastewater (Dlangamandla, 2016; Debik & Coskun, 2009). The chemical constituents present in the wastewater mostly originate from the cleaning and sanitizing stages, stages which while accounting for a large proportion of the water consumed, are crucial for ensuring that the process is hygienically safe, and the poultry products are fit for human consumption (Mohammed, 2014; Department of Agriculture and Rural Development, 2009). The choice of treatment method and design of equipment used in the wastewater treatment process are influenced by the quality and quantity of wastewater generated (Molapo, 2009). Table 5.2 summarizes the characteristics of poultry slaughterhouse wastewater, including treatment methods used.

Table 5.2: Poultry slaughterhouse wastewater characteristics and treatment methods used

Treatment process	Parameters					Reference
	tCOD (mg/L)	BOD_5 (mg/L)	pH -	TSS (mg/L)	FOG (mg/L)	
Static Granular reactor	3137-7864	1543-5732	5.6-6.9	840-2355	-	Oh, 2012
Sequencing Batch Reactor and Chemical DAF	2060-4380	1559-26983	6.3-7.0	480-1230	131-261	De Nardi *et al.*, 2011
Ultra-Filtration	3610-4180	1900-2200	-	2280-2446	289-389	Yordanov, 2010
Static Granular reactor	4200-9100	-	5.6-8.1	1850-3750	-	Debik & Coskun, 2009
Chemical DAF and Up- flow Anaerobic Sludge Bed Reactor (UASB)	2360-4690	1190-2624	6.5-7.0	640-1213	249-702	Del Nery *et al.*, 2007
UASB	2000-6200	1300-2300	6.3-6.6	850-6300	40-600	Caixeta *et al.*, 2002

Treatment methods – such as physical, chemical, and biological processes (Kiepper, 2001) – have been utilized for the treatment of poultry slaughterhouse wastewater. Each process type has both unique treatment advantages as well as operational limitations. Table 5.3 provides a brief summary of these treatments methods.

Table 5.3: Poultry slaughterhouse wastewater treatment technologies (Molapo, 2009; Mittal, 2005; Kiepper, 2001; Masse, 2000; Johns, 1995)

Treatment Type	Physical Treatment	Chemical Treatment	Biological Treatment
Application	Removal of suspended solids, fats oil and grease	Removal of fats, suspended solids, nutrients	Removal of organic matter (COD and BOD), pathogens
Treatment Method	Screening, fat traps, catch basins, settling	Dissolved air flotation (DAF) chemical flocculation, electrocoagulation	Activated sludge systems, anaerobic and aerobic systems

Biological treatment methods primarily involve the removal of organic compounds and deactivation of pathogens from wastewater using microorganisms (Molapo, 2009). There are two types of biological treatment processes, namely aerobic and anaerobic treatment systems. Both processes require sufficient contact time between the wastewater and the microorganisms for effective treatment (Kiepper, 2001). Anaerobic treatment reduces organic compounds to methane and carbon dioxide using microorganisms in the absence of molecular oxygen (Mittal, 2005). Poultry slaughterhouse wastewater is well-suited to anaerobic treatment because it contains high concentration of organic compounds (Debik & Coskun, 2009). Treatment processes included in this category are lagoons, anaerobic contact (AC) reactors, up-flow anaerobic sludge blanket reactors (UASB), expanded granular sludge bed reactors (EGSB), static granular bed reactors (SGBR) and anaerobic filter (AF) processes.

In the food processing industry, anaerobic treatment technology is one of the most widely used treatment methods due to its advantages of treating high strength wastewater (Karnchanawong & Phajee, 2009). Additionally, high and low rate anaerobic digestion systems have been used in treating poultry slaughterhouse wastewater due to their ability to handle high concentrations of particulate matter and FOG. The up-flow anaerobic sludge bed (UASB) reactor is also widely used to treat poultry slaughterhouse wastewater. Debik *et al*. (2009), using the static granular bed (SGBR) reactor to treat poultry slaughterhouse wastewater, obtained an average tCOD removal of 95%. Similarly, Del Nery *et al*. (2005) obtained a 65% total and 85% soluble tCOD reduction at an average organic loading rate (OLR) of 1.64 kg COD/m^3.day using a full scale UASB reactor. For high treatment efficiency, these treatment systems can be combined with other systems to improve efficiency. For example, De Nardi *et al*. (2008) investigated the use of a Dissolved Air Floatation (DAF) as a pre-treatment prior to the UASB reactor in order to lower the influent FOG and suspended solids load, a strategy which improved the UASB functionality. Yodanov (2010) reported tCOD removal greater than 94% for treatment of poultry slaughterhouse using ultra-filtration membrane systems.

In this study, the feasibility of using a two-stage process in which a mesophilic Static Granular Bed Reactor (SGBR) coupled with to a UF membrane system was investigated. The use of this two-stage system has not yet been applied at an industrial scale in SA, particularly for the treatment of poultry slaughterhouse wastewater. The purpose of this study, then, was to evaluate the treatment efficiency of a lab-scale SGBR anaerobic digester coupled with a UF membrane system for effective tCOD reduction for poultry slaughterhouse wastewater, in order for the treated wastewater to comply with the City of Cape Town (CCT) by-law discharge standards for assessing the quality of industrial wastewater.

5.2 Objectives

The objectives of this part of the study were as follows:

- to evaluate the effectiveness of the down-flow SGBR coupled with UF membrane configuration as an alternative to the up-flow EGSB reactor coupled with anoxic aerobic bioreactor in treating poultry slaughterhouse wastewater;
- to investigate if there is a need for a pre-treatment stage prior the anaerobic digestion stage to improve the performance of the SGBR configurations; and
- to identify limitations and operational deficiencies of the SGBR reactor configurations for the treatment of poultry slaughterhouse wastewater.

5.3 Material and methods

5.3.1 Experimental set-up and equipment

Figure 5.1 represents the laboratory bench-scale SGBR anaerobic digester coupled with the UF membrane system that was operated for 64 days. The purpose of the bench-scale SGBR reactor was to reduce the organic load of the feed after the effluent passed through the UF membrane systems. The bench-scale SGBR anaerobic digester consisted of a polyvinyl chloride (PVC) cylinder-shaped reactor with a total working volume of 1.53 L and an inner diameter and height of 0.071 m and 0.5867 m, respectively.

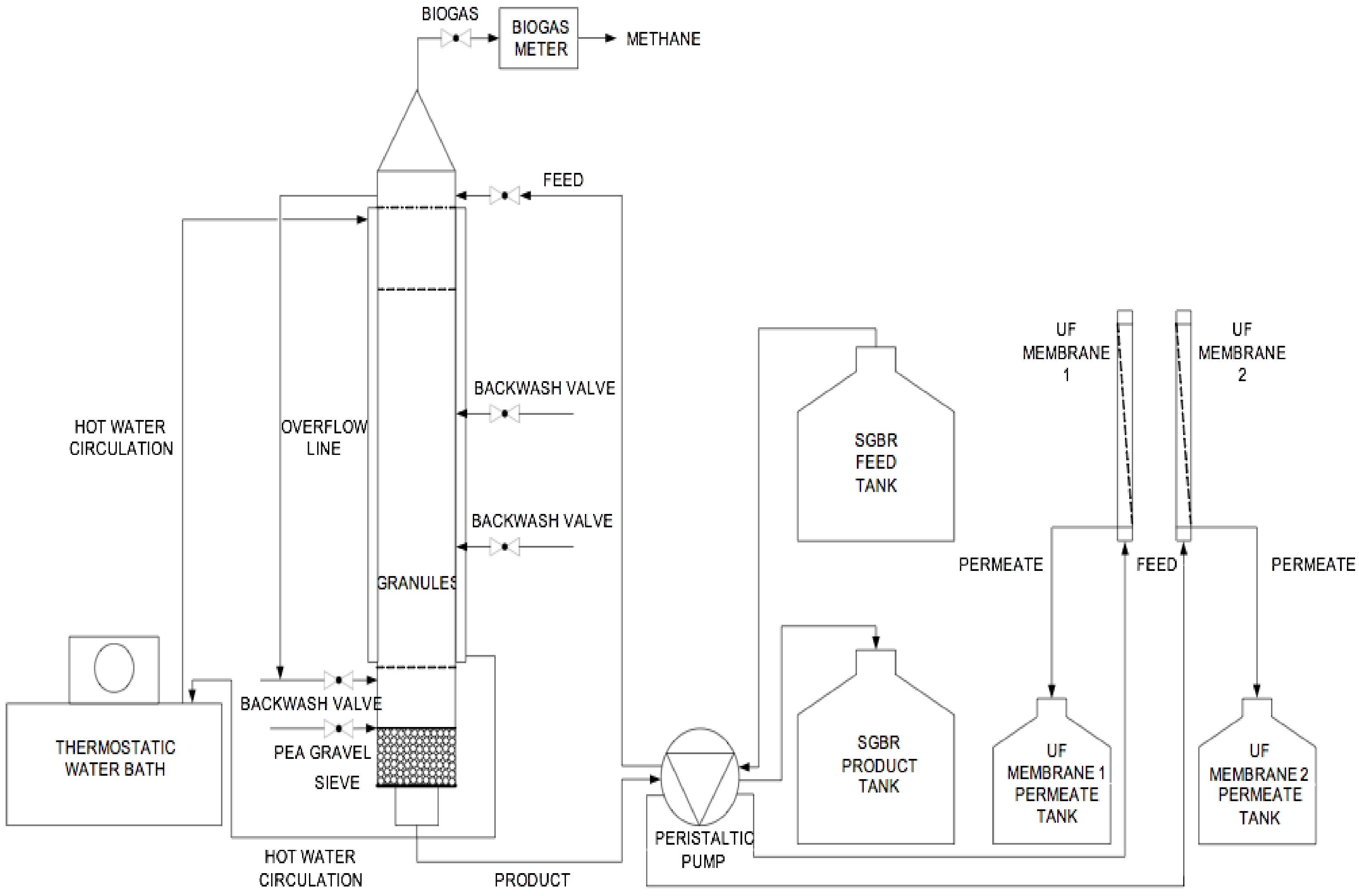

Figure 5.1: Schematic diagram for the laboratory bench-scale SGBR coupled with ultra-filtration (UF) membrane system

Separate 5 L polypropylene sample containers were used to store wastewater prior to and after treatment. A perforated PVC pipe was placed at the top of the SGBR to distribute the feed across the entire cross-section of the reactor. Pea gravel with an average diameter of 5 mm was used as an under-drain to prevent granular sludge washout and clogging of under-drain pipes. A 2-mm grit sieve was positioned at the bottom of the SGBR to retain the pea gravel. Silicone tubing was used for an overflow line and a backwash system was installed for declogging. The influent was fed at the top of the reactor using a multi head Gilson (Germany) peristaltic pump and the effluent was simultaneously withdrawn from the bottom of the SGBR at the same rate. The reactor operated at a mesophilic temperature ranging between 35 and 37°C. The water jacket temperature was regulated and circulated using a thermostatic water bath. The reactor was also insulated to prevent heat losses to the environment. The biogas produced was collected in a 0.50 L plastic Tedlar bag through an outlet port installed at the top of the SGBR. The SGBR reactor was backwashed using the SGBR effluent using the backwash line to remove suspended solids accumulating on the pea gravel to prevent the system from clogging.

5.3.2 Slaughterhouse wastewater

The poultry wastewater was collected from a slaughterhouse located in the Western Cape, SA. The characteristics of the wastewater are summarized in Table 5.2 which lists average values of parameters quantified over a 9-week sampling period. All measurements were performed according to standard methods (APHA, 2005).

Table 5.2: Characteristics of the wastewater from a poultry slaughterhouse in the Western Cape, South Africa (quantified, as no published data available in SA)

Parameter	Unit	Poultry slaughterhouse waste water	
		Range	Average
pH		6.5-8.0	-
Alkalinity	mg/L	0- 489	489
Total chemical oxygen demand	mg/L	2133-4137	2903
Soluble chemical oxygen demand	mg/L	595-1526	972
Biological oxygen demand	mg/L	1100-2750	1667
TKN	mg/L	77-352	211
Ammonia	mg/L	29-51	40
TKN	mg/L	77-352	211
Total Phosphorus	mg/L	8 – 27	17
Fats, oil and grease	mg/L	131-684	406
Total dissolved oxygen	mg/L	372-936	654
Total suspended solids	mg/L	315-1273	794
Volatile suspended solids	mg/L	275-1200	738
Soluble proteins	mg/L	0-368	72
Volatile fatty acids	mg/L	96-235	235

5.3.3 SGBR inoculation and start-up procedure

The SGBR was inoculated with 0.95 L of anaerobic granular sludge collected from a full-scale up-flow anaerobic sludge bed (UASB) reactor operated at a local brewery (Newlands Brewery, Western Cape, SA). Poultry slaughterhouse wastewater (collected from a slaughterhouse in the Western Cape, SA), with a volume of 0.43L, was also added to the SGBR to initiate the process. A Gilson peristaltic pump was fed the wastewater into the SGBR. Dry milk solution prepared with distilled water, with a tCOD concentration of 2000 mg/L, was used as feed during the acclimation period of 48 hr.

5.3.4 SGBR operating conditions

Collected poultry slaughterhouse wastewater samples were refrigerated at a temperature of 4˚C. The poultry slaughterhouse wastewater was diluted with distilled water to prevent shock loading during the acclimatization period. During the last 36 days of the SGBR operation, the bioreactor was fed with the undiluted poultry slaughterhouse wastewater. After the acclimation period of 48 hr, the flow rate was adjusted to 27.8 mL/h (HRT to 55 h) with the system then allowed to reach steady state. The HRT of 55 h was maintained for a total of 44 days with an average OLR of 1.01 g COD/L.day. To start the process, the SGBR was fed with 50% of the diluted poultry slaughterhouse wastewater for the initial 19 days (1:1 ratio), followed by diluted poultry slaughterhouse wastewater with a concentration of 67% (2:1 ratio) for the subsequent 9 days. Thereafter, undiluted poultry slaughterhouse wastewater was fed to the SGBR for an additional 16 days while maintaining an HRT of 55 h.

The HRT was further reduced to 40 h during the last 21 days of operation by increasing the feed flow rate to 38.3 mL/h. The average OLR of the undiluted feed used during this period was 3.14 g COD/L.day. Table 5 provides the operating conditions governing the continuous operation of the SGBR over a period of 64 days. The treated wastewater generated by the SGBR was used as the feed for the bench-scale UF membrane post-treatment system.

Table 5.3: Operating conditions (HRT and OLR) for the SGBR system over a period of 64 days

Dilution (%)	Operating Time (days)	Flow rate (mL/h)	HRT (hrs)	OLR (g COD/L.day)
50	1-19	27.8	55	0.56
67	20-28	27.8	55	0.67
None	29-44	27.8	55	1.73
None	45-64	38.3	40	3.14

5.3.5 The ultra-filtration (UF) membrane system

An inorganic membrane with an inner diameter of 2 mm and an outer diameter of 3 mm was utilised as a post-treatment system for the SGBR reactor. The membrane consisted of alpha aluminium oxide (Al_2O_3) ceramic material with a membrane pore size of 40 nm. The UF membranes were operated under a dead-end flow configuration. The UF membranes were replaced after 7 consecutive days due to flux reduction. The clogged UF membranes were then back-washed to remove suspended solids with the membrane surface appearing free from the gel-layer deposit.

5.3.6 Analyses of poultry slaughterhouse wastewater

The performance of the SGBR was monitored using untreated and treated wastewater, focusing on analyses of the following: pH, temperature, conductivity, TDS, salinity, turbidity, TSS and tCOD. Samples of the SGBR feed and product streams including UF permeate were taken every second day (i.e. Mondays, Wednesdays and Fridays) for in-house analyses in duplicate. A weekly sample of the SGBR product and UF permeate was taken to an external South African National Accreditation System (SANAS) accredited laboratory (Scientific Services, City of Cape Town, South Africa) for tCOD, FOG, TSS, VFA and alkalinity analyses.

5.4 Results and discussion

The findings of this study represent the SGBR operation for different OLRs applied under different HRTs for a period of 64 days. The SGBR effluent was used as the feed for the UF membrane system.

5.4.1 Variation of OLR and HRT on the SGBR reactor

The SGBR coupled with UF membrane system was operated continuously for a period of 64 days at different HRTs and OLRs. The poultry slaughterhouse wastewater was diluted with distilled water to prevent shock loading during the acclimatization stage of 48 hr. The HRT of 55 h was maintained for a total of 44 days with an average OLR of 1.01 g COD/L.day. For the first 19 days, the SGBR was fed with 50% diluted poultry slaughterhouse wastewater and subsequently, diluted poultry slaughterhouse wastewater with a concentration of 67% (2:1) was fed to the SGBR for 9 days. Thereafter, undiluted poultry slaughterhouse wastewater was fed for a period of 16 days at an HRT of 55 h. The HRT was thereafter reduced to 40 h for the last 21 days, with the average OLR of the undiluted feed used during this period at 3.14 g COD/L.day.

The tCOD in the SGBR feed ranged between 1223 to 9695 mg/L with an averaged tCOD of 4681 mg/L, as shown in Table 5.4. The COD was used in this study as a comparative parameter to quantify system performance and to monitor the effect of the OLR throughout the study. The tCOD of the SGBR product ranged between 15 and 940 mg/L, with an average of 263 mg/L being observed.

Table 5.4: Composition of the raw poultry slaughterhouse wastewater (feed) and the SGBR product (effluent)

		Composition of SGBR feed			Composition of SGBR product		
Parameters	**Units**	**Minimum**	**Maximum**	**Average**	**Minimum**	**Maximum**	**Average**
pH	-	6.31	7.26	6.78	7.30	7.97	7.61
Temperature	ºC	19.3	22.5	21.2	18.7	23.5	21.1
Conductivity	µS/cm	1384	2040	1708	1461	1916	1710
TDS	mg/L	986	1450	1213	1040	1360	1216
Salinity	mg/L	733	1040	887	769	1010	888
Turbidity	NTU	72.6	841	397	9.06	50.8	28.4
TSS	mg/L	734	4992	2651	21	111	53
COD	mg/L	1223	9695	4681	15	940	263

5.4.2 SGBR performance and COD reduction

The average tCOD removal by the SGBR for the 64-day period was found to be 93%. The tCOD removal during the first week of operation fluctuated due to the microbial culture acclimatizing to the wastewater being used. Thereafter, the tCOD removal remained relatively constant with removal efficiency greater than 90%. The COD removal fluctuated between day 50 and 64, when the HRT was decreased to 40 h and the OLR increased to 3.14 g COD/L.day. The decrease in tCOD removal during this period may be attributed to the system destabilization after the increase in the organic load, as well as the backwashing process. The average tCOD removal during this period was 90%, still relatively high. The tCOD removal obtained over the 64 days was between the averages of 37% during bioreactor start-up, reaching a maximum of 93% during steady state periods, respectively, as seen in Figure 5.4.

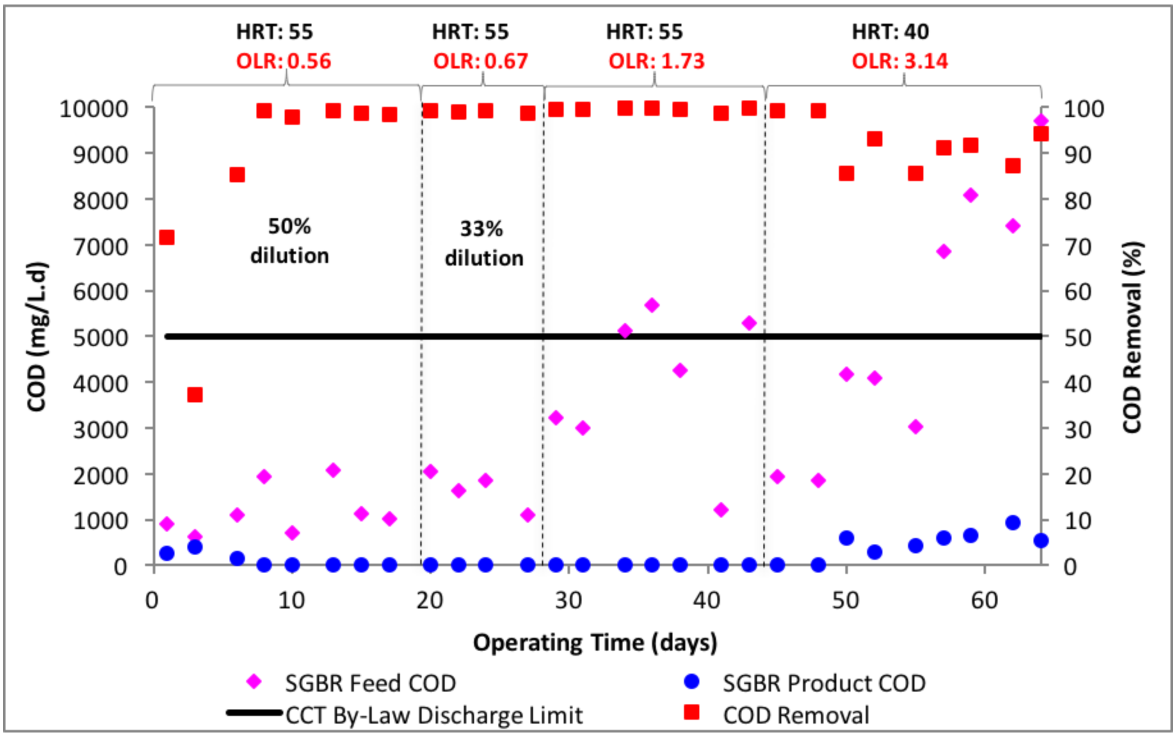

Figure 5.4: COD removal efficiency of the SGBR reactor at different HRT and OLR

This treatment efficiency correlates to a study conducted by Evans (2004), who reported a tCOD removal range of 92 to 94% for a pilot-scale SGBR and 83.7 to 95.7% for a lab-scale SGBR. Debik and Coskun (2009) also reported tCOD removal efficiencies varying between 85 and 97% for the treatment of poultry slaughterhouse wastewater in a lab-scale SGBR operating at an HRT of 60 h. For HRTs of 40 and 36 hr, tCOD removal was >90% and >93%, respectively.

5.4.3 Compliance: COD Industrial discharge standard

The tCOD of the SGBR feed and SGBR product was compared to the City of Cape Town (CCT) discharge standard, as shown in Figure 5.4 above. The results showed that the average tCOD concentration of the poultry slaughterhouse wastewater obtained from the industrial partner did not meet the maximum limit permitted for discharge as the average tCOD exceeded 5000 mg/L (CCT Wastewater and Industrial Effluent By-Law, 2013). After the anaerobic treatment using the SGBR, the tCOD concentration was significantly reduced, with an average tCOD removal of 93% over the 64-day operational period as demonstrated in this part of the study, resulting in the SGBR product being below or within the required discharge standards.

5.4.4 TSS removal efficiency

The TSS was measured to determine the concentration of the insoluble organic and inorganic matter suspended in the poultry slaughterhouse wastewater. The TSS was also used in this study to evaluate the performance of the SGBR under varying HRTs and OLRs, as shown in Figure 5.5, indicating the SGBRs feed TSS, SGBRs TSS in the product and the averaged TSS percentage removal. The TSS of the SGBR feed ranged between 734 and 4992 mg/L, with treatment effectively reducing it to a range between 20 and 320 mg/L. The TSS percentage removal over the 64-day period ranged between 76 and 99%, with an average value of 95%. The minimum TSS removal observed was 76%, achieved during the first week of the SGBR operation, specifically during days 3 to 5, since the system was still stabilizing to the PSW. On day 8, the TSS removal exponentially increased to 91% and remained relatively steady throughout the duration of the SGBR operation. The average TSS removal for the HRT of 55 h and 44 h was found to be between 93 to 98%, respectively, indicating the capacity and efficiency of the designed SGBR system, particularly for the treatment of high strength wastewater used in this study. For comparative analysis, Oh *et al*. (2014) only reported a TSS removal of 80% for a HRT of 48 hr for a pilot-scale SGBR used for treating dairy wastewater at ambient temperature. Furthermore, reducing the HRT to 40 hr did not have an adverse effect on the SGBR performance with regards to TSS removal. Despite the variation in the TSS of the feed, due to variations in the quality characteristics of the wastewater sampled, the SGBR was consistent in reducing the TSS. However, the TSS of the SGBR product was determined to not only be dependent on the anaerobic digestion process but also the physical attributes of the design used, which facilitated the retainment of the suspended solids in the granular bed. This might be disadvantageous when the system is operated for elongated periods, as the accumulation of TSS might hamper the distribution and thus the wastewater flow within the system. However, based on the operability efficiencies of the system, as suggested in this part of the study, the down-flow operation of the SGBR was hypothesized to aid the removal of suspended solids since the granular bed and pea gravel act as a filtration system.

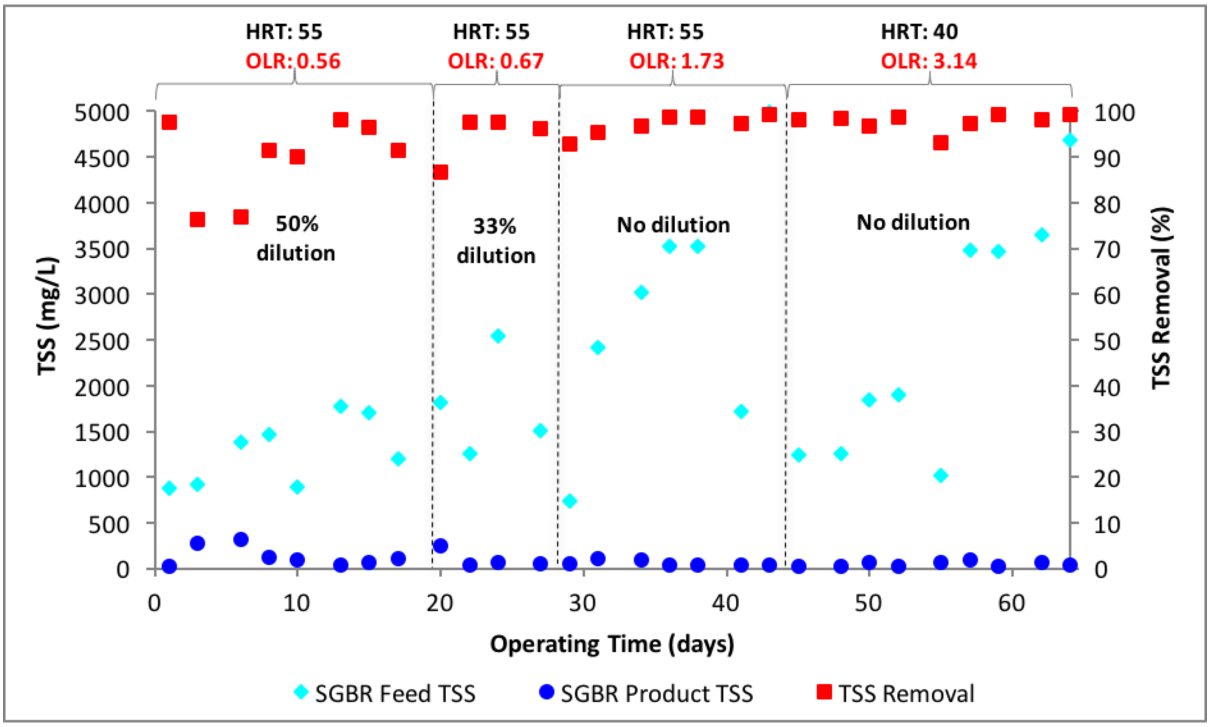

Figure 5.5: Variation of TSS concentration at different OLR and HRT and TSS removal efficiency of the SGBR reactor

5.4.5 pH and temperature variations

The influent pH varied from 6.4 to 7.3 with an average of 6.8, while the effluent pH varied from 6.4 to 7.9 with an average of 7.5. The pH of the effluent was at a favourable range (6.5 to 8) for methanogenic organisms, suggesting that biogas generation might be favoured.

5.4.6 VFA/Alkalinity ratio

Parameters such as alkalinity, volatile fatty acid and pH are important in monitoring the stability of an anaerobic digester. VFA/alkalinity ratio less than 0.3 indicates a stable operation, while a ratio 0.3 to 0.4 indicates potential system operational unsuitability, which will then require corrective action. A VFA/alkalinity ratio exceeding 0.8 results in the inhibition of the methanogens as VFA accumulation can result in acidification of the anaerobic digester, conditions which are unsuitable for methanogens. The VFA/alkalinity ratio range was 0.01 to 0.14, indicating that the system was stable throughout the operation as the ratio was below 0.3.

5.4.7 Ultra-filtration (UF) membrane system

Table 5.5 shows the results for the UF membrane process on pollutant reduction: the further reduction in pollutant concentration from SGBR reactor product. Overall, such systems are used as tertiary treatment systems, particularly if the treated wastewater is to be recycled and used as process water. The UF treatment of the poultry wastewater from the SGBR reactor was monitored using tCOD, TSS and FOG pollution indices. The results indicated that the average retention efficiency was further increased by 64%, 88% and 48% for tCOD, TSS and FOG, respectively. The values of the pollution indices are below the CCT discharge limit standards. The results obtained were deemed encouraging, as the coupling of the SGBR with a UF membrane treatment process could further ensure sustainable water usage in the poultry industry, particularly in SA.

Table 5.5: Ultra-filtration systems permeate composition

Parameter	Units	Average SGBR Product	Averaged UF Permeate	Average Retention (%)
COD	mg/L	162±20	59±6	64
TSS	mg/L	29±3	4±3	88
FOG	mg/L	60±47	31±18	48

5.4.8 Overall tCOD, TSS and FOG removal of the SGBR and UF membrane

Table 5.6 below illustrates the overall tCOD, TSS and FOG removal efficiency of the system (coupled SGBR and UF membrane systems). These were determined from the SGBR feed and permeated from the UF membrane system. The overall COD, TSS and FOG removal of the system were 98.7%, 99.8% and 92.4%, respectively.

Table 5.4: Overall tCOD, TSS and FOG of the SGBR and UF system

Parameter	Units	Averaged SGBR Feed	Averaged UF Permeate	Overall % Removal
tCOD	mg/L	4681$\pm$4236	59$\pm$6	98.7
TSS	mg/L	2651$\pm$2129	4$\pm$3	99.8
FOG	mg/L	406$\pm$200	31$\pm$18	92.4

5.5 Summary

The South African poultry industry has grown exponentially in recent years due to an increased demand for poultry products. As a result, poultry plants consume large volumes of potable water in their efforts to ensure the production of hygienically safe poultry products. Furthermore, the poultry industry generates high strength wastewater which can be treated successfully at low cost using anaerobic digesters. In this part of the study, the performance of a bench-scale mesophilic Static Granular Bed Reactor (SGBR) containing anaerobic granules coupled with an ultra-filtration (UF) membrane system as a post-treatment system was investigated. The poultry slaughterhouse wastewater was characterized by a chemical oxygen demand (tCOD) of 1223 to 9695 mg/L, an average biological oxygen demand (BOD) of 2375 mg/L and an average FOG of 554 mg/L. The SGBR anaerobic reactor was operated for 9 weeks at different hydraulic retention times, (HRTs), for example, 55 and 40 hrs, with an average organic loading rate (OLR) of 1.01 and 3.14 g COD/L.day. The SGBR results showed an average tCOD, total suspended solids (TSS) and FOG removal of 93%, 95% and 90% respectively, for both organic loading rates (OLRs). The UF post-treatment results showed an average of tCOD, TSS and FOG removal of 64%, 88%

and 48%, respectively. The overall tCOD, TSS and FOG removal of the system (SGBR and UF membrane) was 98%, 99.8%, and 92.4%, respectively. The results of the combined SGBR reactor coupled with the UF membrane showed a potential to ensure environmentally friendly treatment technology for poultry slaughterhouse wastewater. Furthermore, the SGBR treated the PSW with high performance without a need for any pre-treatment stage, indicating its ability to treat PSW with high OLRs as compared to the up-flow EGSB reactor, which generated sludge washout. The operational deficiency experienced by the SGBR at high OLRs, such as increase in head loses on the granular sludge resulting in clogging of the underdrain, was alleviated by implementing a periodic backwash to remove fine particles.

Due to limited variation of operational parameters such as HRT, OLRs and short operation time explored in Chapter Five, as the experiment was momentarily suspended at day 64 due to university shutdown ("Fees Must Fall students protest movement"), a re-run of the SGBR was conducted with a special focus on modelling the substrate (COD) removal using the Grau second-order and modified Stover-Kincannon model in Chapter Six. The re-run was operated with a 2 L SGBR working volume over a period of 110 days varying (n=4) HRTs and average OLRs (n=4). In addition, the influent was filtered to remove feathers and suspended solids prior the SGBR.

Acknowledgement

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CHAPTER SIX

RESULTS

Part of these results was published as a book chapter for conference proceedings as:

Basitere, M., Njoya, M., Rinquest, Z.M., Sheldon, M.S. & Ntwampe, S.K.O. 2017. Performance and kinetic Analysis of a Static Granular Bed Reactor for treating Poultry Slaughterhouse wastewater. In *Frontiers International Conference on Wastewater Treatment and Modelling*, 225-229. Springer, Cham (Available Online 05 May 2017; DOI: 10.1007/978-3-319-58421-8_35.

Supplementary data is supplied in Appendix D

NB: This section is a re-run of the SGBR reactor varying different HRT and OLRs

6. PERFORMANCE EVALUATION AND KINETIC PARAMETER ANALYSIS FOR A STATIC GRANULAR BED REACTOR (SGBR) FOR TREATING POULTRY SLAUGHTERHOUSE WASTEWATER AT MESOPHILIC CONDITIONS

6.1 Introduction

In South Africa, the poultry product industry consumes a significant quantity of potable water ranging from 4.2 to 16.7 m^3 per tonne of live carcass weight for slaughtering and processing birds, including the cleaning and sanitising of equipment (Park *et al*., 2012). The wastewater volumes generated from the poultry slaughterhouse range from 2.0 to 5.1 L per tonne of live weight kill (LWK) with an average of 3.9 m^3 per tonne LWK (Oh, 2012), resulting in the generation of an excessive volume of wastewater containing a high concentration of organic matter quantifiable as biochemical oxygen demand (BOD_5) and/or total chemical oxygen demand (tCOD). Poultry slaughterhouse wastewater (PSW) contains phosphorous and nitrogenous compounds, including blood, fats, oil, grease (FOG) and proteins (Debik & Coskun, 2009). The presence of suspended and colloidal matter such as proteins, fats and cellulosic matter, may inhibit the performance of an anaerobic digester, which is attributed to the un-degradability and insolubility of such organic matter (Johns, 1995; Torkian, 2003). To circumvent severe environmental pollution and subsequent municipal disposal levies, the PSW must be efficiently treated prior to discharge into the local municipal sewage system or the receptive fresh water sources.

For suitable treatment, anaerobic digestion (AD) technology is described as one of the most favourable methods for the treatment of high strength agricultural wastewater due to its reduced footprint, high influent treatment rates, low sludge production and reasonable operating costs (Jijai *et al*., 2015). Due to the dual benefit of Ads – reducing environmental pollution and generating biogas for energy needs – it is regarded as an attractive treatment option (Harikishan *et al*., 2003). The advantages of AD technology include its ability to function independent of electricity supply, thereby making it suitable for some developing countries such as South Africa (Turkdogan-Aydinol, 2011). Furthermore, the application AD technology in enviromental engineering applications is motivated by the need for energy efficiency and CO_2 emmision reduction to mitigate against global warming effects (Van Lier, 2008).

The first generation AD to be widely used in the wastewater treatment enviroment is the septic tank system, with its application mainly used as a pre-treatment system for sewage (Al-Jamal *et al*., 2009). Over the recent decade, advances in AD process technology developments has led to concommitant improvements in new AD technologies culminating in their ability to treat low to high strength wastewater. The newly developed AD biorectors include the anaerobic filters, anaerobic contact process, up-flow anaerobic sludge blanket (UASB) biorector, and expanded granular bed (EGSB) biorectors. A newly developed bioreactor known as the Static Granular Bed Reactor (SGBR), developed by Ellis and Mach (2004) at the Iowa State University Environmental Laboratory, has shown potential to treat high strength wastewater with high efficiency. The SGBR design incorporates highly active, dense microbial granules in a simple down-flow configuration. And because of this down-flow configuration, the SGBR allows for an improved retention of anaerobic biomass and a simpler influent distribution system while recovering biogas easily, separating the anaerobic granules from treated wastewater due to the counter-current flow between the gas generated and liquid phases (Park *et al*., 2009).

Furthermore, the down-flow operation allows suspended solids in the influent to be filtered through the granular bed (Oh, 2012) with minimal mechanical agitation and a mixing system or recirculation system, as it relies on biogas-induced mixing which reduces short circuiting and dead-zones within the reactor. As such, the SGBR can treat a variety of types of wastewater at high organic loading rates (OLRs) and short HRTs, with few inadequecies observed in studies using laboratory scale bioreactors. Debik *et al*. (2009) reported on the perfomance of the SGBR and its suitability in treating PSW, achieving 90% tCOD reduction. Similarly, Evans and Ellis (2007) reported tCOD removal of 91% treating synthetic wastewater composed of sucrose and non-fat dry milk, an improved system perfomance when compared to an UASB reactor. Roth and Ellis (2004) reported tCOD removal efficiency of 90% at OLRs of 1.9 to 4.55 Kg tCOD/m^3d when treating pork slaughterhouse wastewater, with Park *et al*. (2012) concurring to such perfomance at OLRs of 0.77 to 12.76 kg/m^3.day, achieving tCOD removal efficiency > 95%.

Generally, modelling plays a valuable role in the design of biological treatment plants. Moreover, modelling of wastewater treatment plants assists in the development of better treatment processes, as it has the potential to lower operation cost through optimization, while solving operational problems (Turkdogan-Aydinol *et al*., 2011).

Additionally, modeling provides of rational basis for process analysis and control strategies to meet the effluent quality requirements at reasonable cost (Yu *et al*., 1998; Turkdogan-Aydinol *et al*., 2011). The model generated to describe bioreactor operation under various operating conditions can be used to scale-up processes from pilot to full-scale plant operations, reducing the generation of complex and laborious experimental data using simplified mathematical expressions (Yetilmezsoy *et al*., 2009). Models developed for ADs must incorporate a variety of bioremediation mechanisms such as hydrolysis, acidogenesis, acetogenesis and methanogenesis, processes which are involved in the biodegradability and transformation of organic matter. These offer insight into reaction mechanisms, thereby assisting in describing specific kinetic parameters which can be used to compare theoretical values with experimental data obtained from monitoring the bioreactor performance (Jijai *et al*., 2016), including prediction of treatment efficiencies for a full-scale bioreactor (Debik *et al*., 2009), a system used for the treatment of PSW using a SGBR at ambient temperature.

Kinetic models that have been successfully employed to simulate substrate utilization rates (i.e. organic matter biodegradation rates for AD processes) include Monod's (Lyberatos, 1999), second-order Grau (Grau, 1975) and the modified Stover-Kincannon kinetic models (Abtahi *et al*., 2013). These models are used for the prediction of tCOD concentrations as a process output, with known input data, at steady-state conditions. The second-order Grau and the modified Stover-Kincannon models have been widely applied for determining kinetic parameters in wastewater treatment processes involving biological mechanisms. These models have also been successfully used in studies involving the treatment of wastewater from the food processing including starch, soybeans and PSW, for which anaerobic contact bioreactors were previously used (Senturk *et al*., 2010; Ahn *et al*., 2000; Yu *et al*., 1998; Debik *et al*., 2009).

This part of the study took an analytical approach to determine kinetic parameters which describe the substrate utilization rates for SGBR treating PSW at mesophilic conditions to most effectively model, and thus evaluate process efficiency, design relationships for the system designed.

6.2 Objectives

The objectives of this part of the study were as follows:

- to evaluate the COD removal rate of the SGBR reactor in treating PSW;
- to evaluate the effect of organic loading rates on process performance of the SGBR; and
- to determine the bio-kinetic parameters, which can be used to predict COD removal from the SGBR using Grau second-order and modified Stover-Kincannon models.

6.3Materials and methods

6.3.1 Inoculum seed and wastewater characteristics

The poultry slaughterhouse wastewater (PSW) was collected from a poultry product process facility in Cape Town, the Western Cape of SA. The characteristics of the PSW (Table 1) indicate a typical high strength wastewater (i.e. PSW in South Africa). The collected wastewater samples were refrigerated (4ºC) prior to use in the experiments. The granular sludge inoculum was collected from a full-scale up-flow anaerobic-sludge bed (UASB) reactor treating brewery effluent at a South African brewery (SAB Miller Plc, Newlands, South Africa).

Table 6.1: Basic parameters of the poultry slaughterhouse wastewater

Parameter	Unit	Range
pH	-	6.5-8.0
Total chemical oxygen demand	mg/L	1427-11708
Soluble chemical oxygen demand	mg/L	595-1526
Fats, oil and grease	mg/L	131-684
Total suspended solids	mg/L	315-1273
Volatile fatty acids	mg/L	96-235
Alkalinity	mg/L	0-489

6.3.2 The SGBR set-up and operation

A laboratory bench-scale polyvinyl chloride (PVC) SGBR AD was used for this study, with experimental set-up illustrated in Figure 6.1. The bioreactor had a total working volume of 2 L with an inner diameter and height of 0.062 and 0.065 m, respectively. The bioreactor was inoculated with 0.4 L of anaerobic granular sludge collected from an industrial-scale UASB reactor operated at a local brewery (to which 1.6 L of PSW and 0.01L of dry milk solution were added). The PSW was passed through a grit sieve (2 mm), and pumice stones (average diameter of 5-20 mm) were used as the under-drain bed to prevent anaerobic granular sludge washout due to pumping effects, (i.e. pulsation). A multi-head Gilson (Germany) peristaltic pump was used to pump the influent to the top of the bioreactor. A similar pump was used to pump the effluent from the reactor to maintain a steady-state operation. The bioreactor was operated under mesophilic temperature (35 to 37˚C) with the influent temperature regulated using a heated water jacket connected to a thermostatic water bath. To avoid clogging and head losses caused by suspended solids (SS) including FOG in the PSW, a backwash-stream containing the treated PSW effluent was used. The HRT of the bioreactor was kept at 55 hr over a period 28 days during the start-up period, increased to 96 hr for a period of 29 days, then subsequently reduced to 48hr and 36 hr, respectively, after a 25 days' interval. After the acclimatization period, the bioreactor was supplied with a 50% diluted influent at both HRTs of 55 hr and 96 hr, which was then reduced to 25% for a further 25 days at an HRT of 48 hr to prevent shock loading. Raw PSW was only supplied after day 84, maintaining such influent feed up to day 110, at HRT of 36 hr. All values reported are average values for the bioreactor used.

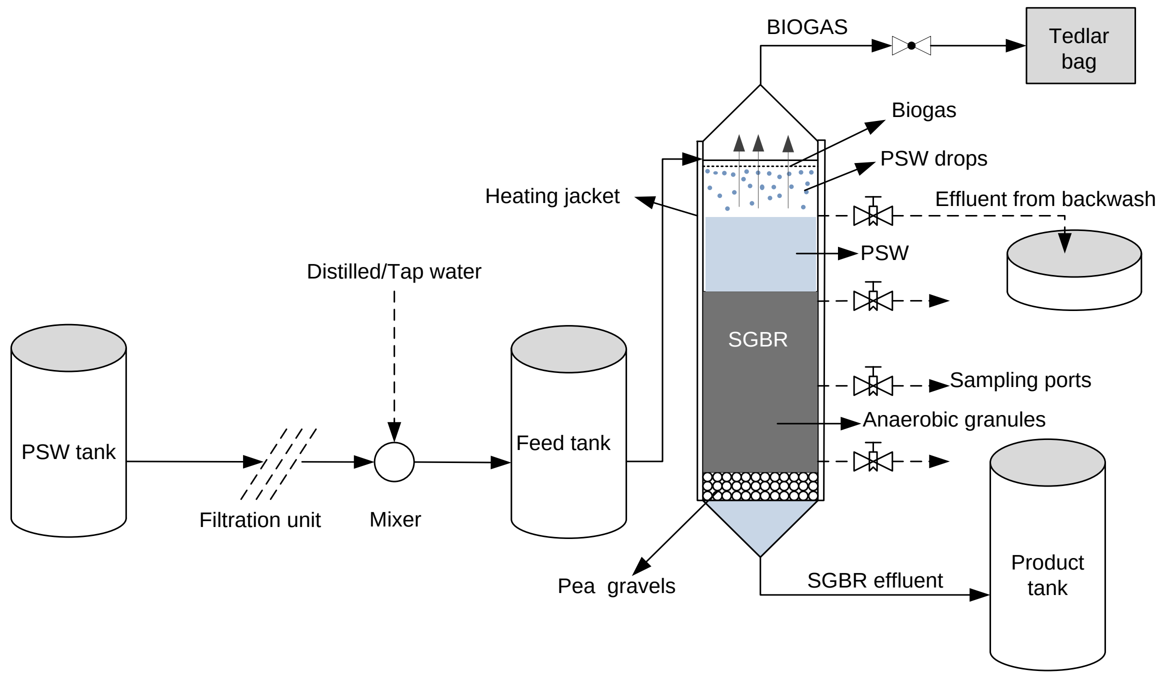

Figure 6.1: Layout of the Static Granular Bed Reactor

6.4Results and discussion

6.4.1 tCOD removal rates

Performance of the SGBR system: tCOD removal rate

Table 6.2 provides a summary of the influent tCOD concentration and tCOD removal rates under various organic loading and hydraulic loading rates. During the first 28 days of the start-up period at 50% (v/v) dilution, the average tCOD removal efficiency of 71% was observed at an HRT of 55 hr and average OLRs 1.17 gCOD/L.day. The high SGBR tCOD removal rate achieved within a short period of time (28 days) was due to anaerobic granules obtained from an operating UASB reactor treating brewery wastewater for seeding the SGBR.

Table 6.2: Performance of the SGBR system treating poultry slaughterhouse wastewater

Dilution	Day	HRT (hr)	COD_{inf} (mg/L)	OLRs(gCOD/L)	COD (%)
50%	1 to 28	55	2606±260.29	1.17	71±4,07
50%	29 to58	96	3126±61.54	0.78	77±1.15
25%	59 to 84	48	3935±221.88	1.97	79±2.04
100%	85 to110	36	6143±1117.65	4.10	85+±2.23
Average			**5039±415.27**	**3.00**	**82±2.37**

Thereafter, the HRT was increased to 96 hr, maintaining a 50% dilution for 29 days and the average tCOD removal efficiency was 77% at an average OLRs of 0.78 gCOD/L.day. The reactor was then fed with 25% PSW for a period of 25 days and HRT of 48 hr at an average OLR of 1.97 gCOD/L.day with an average tCOD removal efficiency of 79% achieved. The system was then fed with undiluted PSW for a period of 25 days at an average OLR of 4.10 gCOD/L.day and HRT of 36 hr achieving an average COD removal rate of 85%. The system experienced head losses resulting in clogging of the pea gravel in the under drain due to high average OLRs between 1.97 and 4.10 gCOD/L.day. Furthermore, a scheduled periodic backwash was initiated for declogging the system to alleviate the operational deficiencies. Despite the operational deficiency experienced, the SGBR maintained higher overall performance with regard to COD removal over a period of 110 days.

Effect of organic loading rates on process performance of the SGBR

Figure 6.2 shows the effect of OLRs on the performance of the SGBR reactor based on tCOD removal efficiency. The SGBR attained an overall average tCOD removal rate of 82% at an average OLR range of 0.78 to 4.10 gCOD/L.day. The variation of the organic loading rate was due to high fluctuation of the influent quality characteristics of the PSW ranged from 1427 to 11708 mg/L. The SGBR was able to cope with hydraulic overloading by reduction of the HRT and the increasing organic shock load caused by an increase in wastewater strength when the reactor was fed with undiluted PSW. Furthermore, high organic removal efficiency was maintained at high OLRs when the reactor was fed with undiluted PSW, indicating the system ability to adapt within a period of 24 hr as indicated by Mach and Ellis (2000). The average tCOD removal efficiency of the SGBR reactor was not decreased with an increase in OLRs, despite clogging of the under-drain operational deficiency, which was alleviated by a periodic backwash.

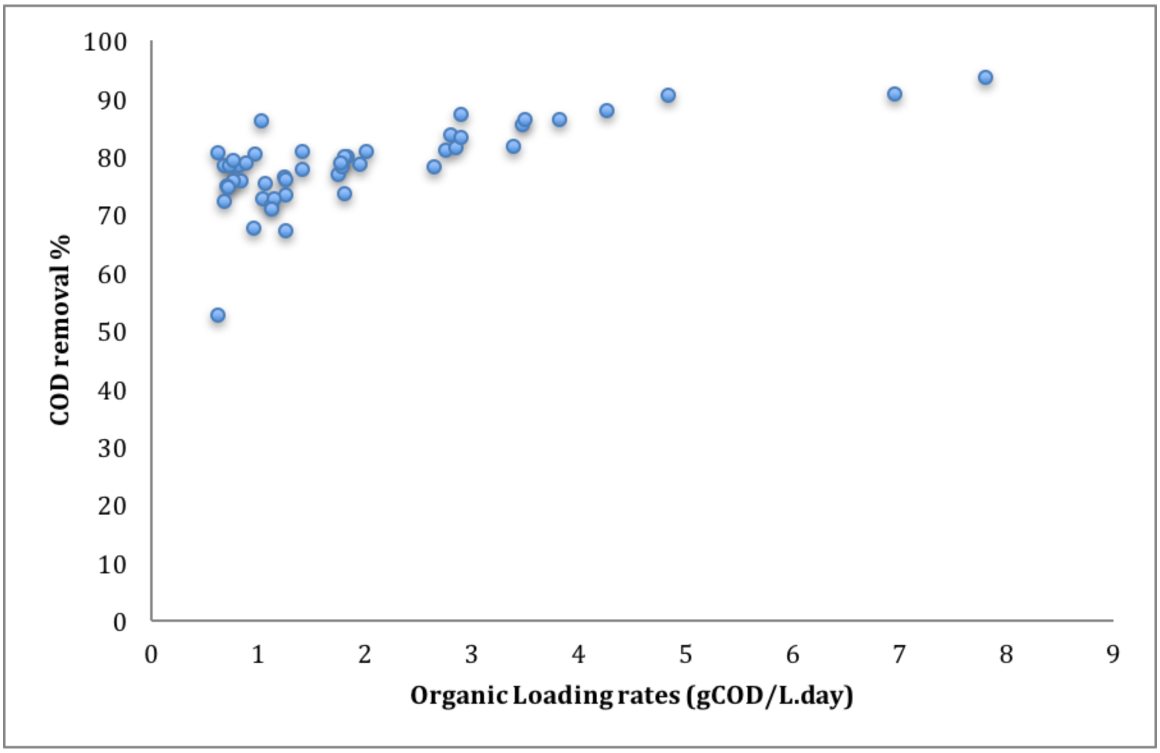

Figure 6.2: tCOD removal efficiency in the SGBR with different OLR

6.5Kinetic model evaluation

6.5.1 Grau second-order multicomponent substrate removal model

The general model, described as a second-order Grau model, is illustrated in Eq. 6.1:

$$-\frac{dS}{dt} = k_s X \left(\frac{S_e}{S_0}\right)^2 \qquad 6.1$$

Where $-\frac{dS}{dt}$ is the COD removal rate (g/L.day); k_s is the substrate removal rate kinetic constant (1/day); X is the average biomass concentration in the bioreactor (g VSS/L); S_e is the effluent substrate concentration; S_0 is the influent substrate concentration (g/L); and $t = \theta_H$ as the hydraulic retention time (HRT).

The subsequent linearized format of Eq. 6.1, within defined boundary conditions $S = S_0$ to S_e and $t = 0$ to θ_H is – see Eq. 6.2:

$$\frac{S_0\theta_H}{S_0 - S_e} = \theta_H + \frac{S_0}{k_s X} \qquad 6.2$$

Which can be further simplified to Eq. 6.3:

$$\frac{S_0\theta_H}{S_0 - S_e} = a + b\theta_H \qquad 6.3$$

Where the substrate kinetics $\left(\frac{S_0}{k_s X}\right)$ represented by letter a and the coefficient b of the HRT representing a value close to 0 reflecting an impossibility of attaining a 0 tCOD. By substituting and/or replacing the tCOD removal efficiency $\left(\frac{S_0 - S_e}{S_0}\right)$ with E, the model can be further simplified to Eq. 6.4:

$$\frac{\theta_H}{E} = a + b\theta_H \qquad 6.4$$

The kinetic parameters used in the Grau second-order model (i.e. *a* and *b* in Eq.6.3) can be determined using a linear trend line to quantify the intercept (*a*) and the slope (*b*) by assessing the interrelatedness between HRT/E, and HRT, as shown in Figure 6.3.

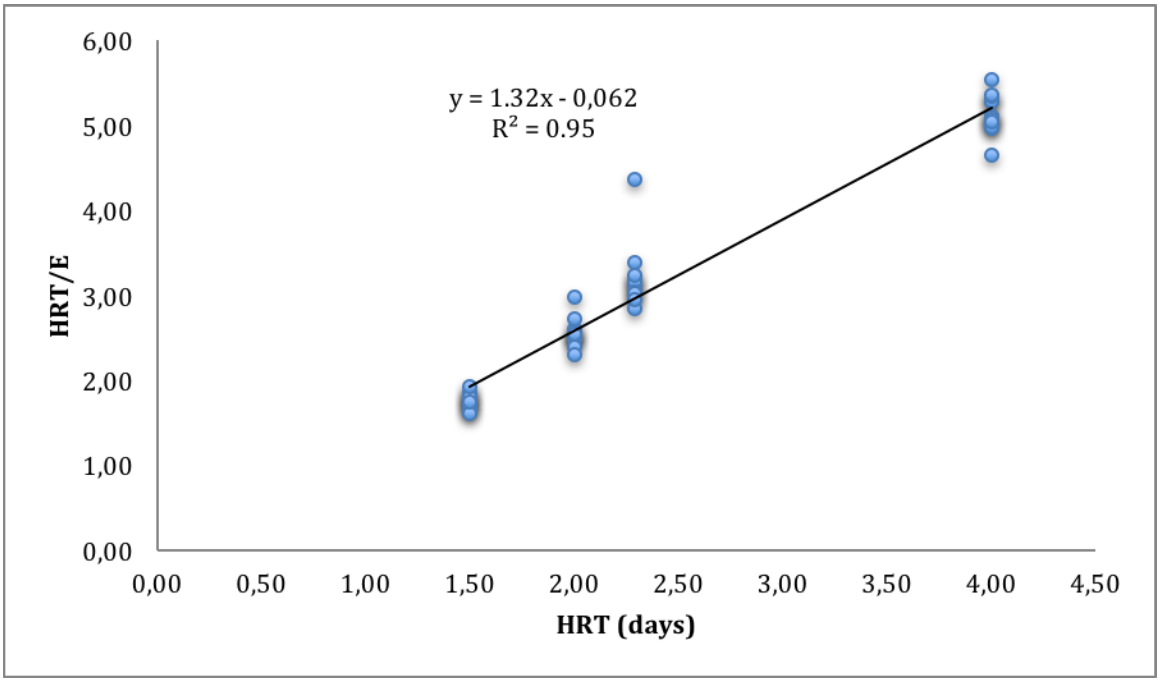

Figure 6.3: Evaluation of Grau second-order model kinetic parameters

The obtained values for a and b were 0.062 and 1.32, respectively, with a correlation co-efficient of R^2 = 0.95 achieved. These values for a and b can be used to predict process efficiency, with the tCOD effluent concentration(S_e) from the SGBR being adequately described by Eq. 6.5:

$$S_e = S_0\left(1 - \frac{\theta_H}{0.062 + 1.32\theta_H}\right) \qquad 6.5$$

The predicted tCOD concentration in the effluent was calculated using Eq. 6.5 based on the Grau second-order kinetic model. Figure 6.4 shows the relationship between the experimental and the predicted tCOD concentration. The predicted values were slightly inconsistent with the experimental data from day 1 to day 80, with the predicted data higher than the experimental data. Furthermore, a major variation was observed between the predicted and experimental data during day 80 to day 110, potentially caused by high and fluctuating influent tCOD concentration as undiluted PSW was fed into the reactor, culminating into an operational deficiency including an increase in head loses to the system, alleviated by the initiation of a backwash stream. Additionally, the Grau second-order model did not account for these operational deficiencies, such as an increase in head losses to the system due to high OLRs of the influent, which might have resulted in the observed high variation between the predicted and experimental data tCOD values. The head losses to the system are due to accumulation of the solids on the pea gravel, which has the potential to result in clogging of the under-drain system, a design flaw receiving further research.

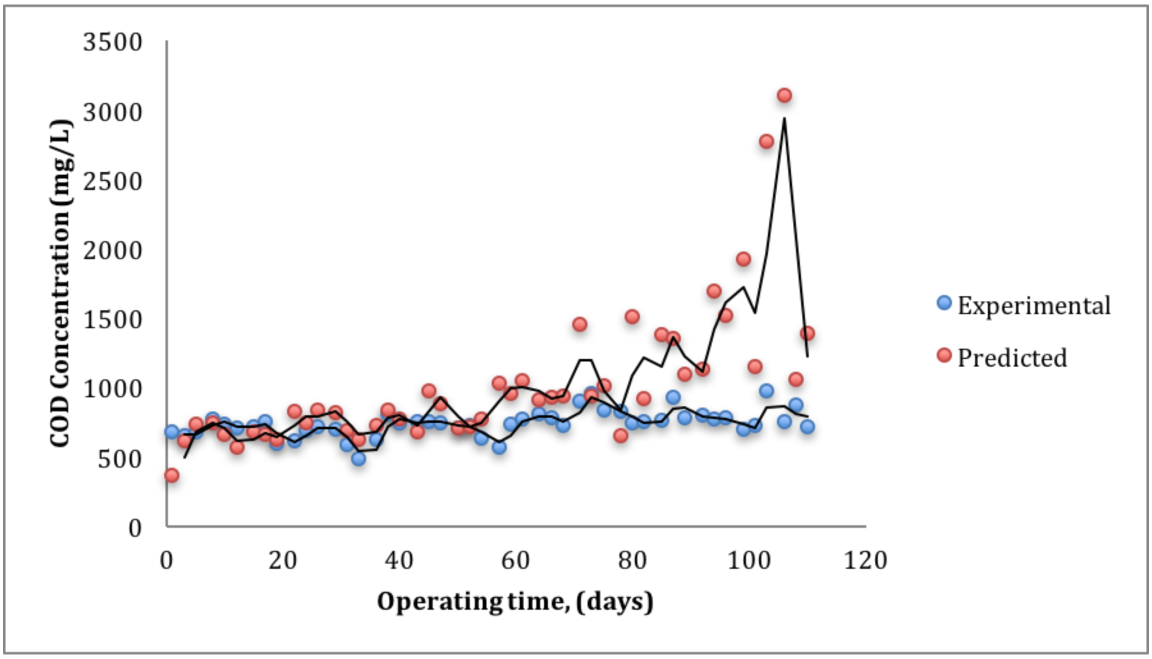

Figure 6.4: Predicted and experimental COD concentration using Grau second-order model

Table 6.3 summarises Grau second-order kinetic constants obtained in this study in comparison to other related studies using the SGBR reactor. The differentiation in the values of kinetic constants obtained might be due to wastewater characteristics and the type of microorganisms dominant in the granular sludge.

Table 6.2: Comparison of kinetic constant of Grau second-order model

Feed substrate	Type of reactor	*a* (per day)	*b*	R^2	References
Poultry slaughter house	SGBR	0.062	1.32	0.95	**This study**
Meat slaughterhouse	SGBR	0.017	1.05	0.99	(Oh, 2012)
Poultry slaughterhouse	SGBR	0.173	1.155	0.95	(Debik, 2009)

6.5.2 Modified Stover-Kincannon model

The Stover-Kincannon model was developed in the 1970 as a design for modelling tCOD removal rate in ADs. The tCOD utilisation rate in this model is expressed as a function of the organic loading rate (Yu *et al*., 1998). This kinetic model was previously used to describe tCOD and total organic carbon (TOC) reduction including biological oxygen demand (BOD_5) in the treated PSW from the digesters (Yu *et al*., 1998). The rate at which the change in tCOD concentration is quantified, requires a steady-state bioreactor operation. Eq. 6.6 represents the model:

$$-\frac{dS}{-dt} = \frac{U_{max}(\frac{S_0}{\theta_H})}{K_B+(\frac{S_0}{\theta_H})} \qquad 6.6$$

Where $-dS/dt$ is defined as the tCOD removal rate (g/L.day); U_{max} is the maximum tCOD removal rate constant (g/L.day); K_B is the saturation constant (g/L.day); *Q* is the flow rate (L/day); *V* is the working volume of the reactor (L); while S_0 and S_e are the influent and effluent tCOD concentrations (g COD/L), respectively.

Eq. 6.6 can also be used to represent the periodical change in tCOD concentration: i.e. $-\frac{dS}{dt}$.

$$-\frac{dS}{dt} = \frac{Q}{V}(S_0\text{-}S_e) \qquad 6.7$$

To evaluate kinetic parameters, the combination and subsequent linearization of both Eq.(s) 6.6 and 6.7, is useful (see Eq. 6.8):

$$\left(\frac{dS}{dt}\right)^{-1} = \frac{\theta_H}{(S_0\text{-}S_e)} = \frac{K_B}{U_{max}}\left(\frac{\theta_H}{S_0}\right) + \frac{1}{U_{max}} \qquad 6.8$$

Comparative analysis between the inverse of substrate utilisation rate against the inverse of the total loading rates shows a linear relationship obtained as depicted in Figure 6.5. The value of the maximum tCOD removal rate constant, U_{max}, including the saturation (affinity) constant, K_B, as depicted in Eq. 6.8, can be obtained from both the slope and the intercept of Eq.6.8. In Figure 6.4, the slope and the intercept were found to be 1.43 and 0.079, respectively, leading to the determination of U_{max} and K_B of 12.70 gCOD/L/day and 18.2 gCOD/L.day, respectively. The predicted value of the maximum tCOD removal (U_{max}) was higher than the maximum OLR of 7.81 gCOD/L.day used during the study. This showed the potential of the SGBR to treat high strength PSW.

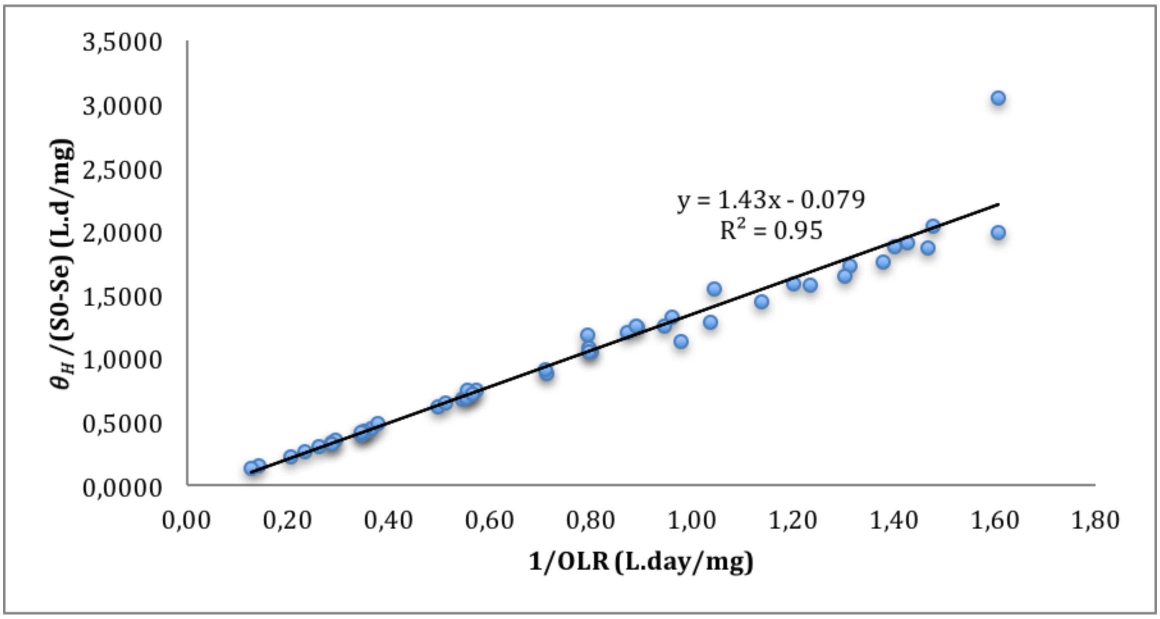

Figure 6.5: Evaluation of modified Stover-Kincannon model kinetic parameters

A substrate balance at a defined reactor volume can be expressed as follows:

$$QS_o = QS_e + V\left(\frac{ds}{dt}\right) \quad 6.9$$

Substituting the Eq. 6.8 for the relationship of $\left(\frac{ds}{dt}\right)$ results in Eq. 6.10 and 6.11 as follows:

$$QS_o = QS_e + V\left(\frac{U_{max}(S_o/\theta_H)}{K_B+(S_o/\theta_H)}\right) \quad 6.10$$

By rearranging to make the effluent concentration, S_e, the subject of the formula, Eq. 6.11 can be obtained:

$$S_e = S_0 - \frac{U_{max}S_0}{K_B+\left(\frac{S_0}{\theta_H}\right)} \quad 6.11$$

Using the value of U_{max} and K_B of 12.70 gCOD/L.day and 18.2 gCOD/L.day, Eq. 6.11 determined predicted values of the effluent tCOD concentration, as seen in Figure 6.7. Figure 6.7 indicates the relationship between the experimental and the predicted tCOD concentration in the effluent. However, the predicted values were slightly inconsistent with the experimental data with the predicted data usually higher than experimental values. A high variation, similar to the one observed from the Grau second-order model, was also observed between day 80 to day 110 when undiluted PSW influent was fed, possibly a result of operation deficiencies caused by an increased OLR and head losses. This variation might have been due tCOD entrapped within the SBGR system due to periodic clogging of the pea gravel by suspended solids and sloughed-off biomass. A similar variation was observed by Oh (2012) in a study modelling the treatment of meat-processing wastewater when using the modified Stover-Kincannon model.

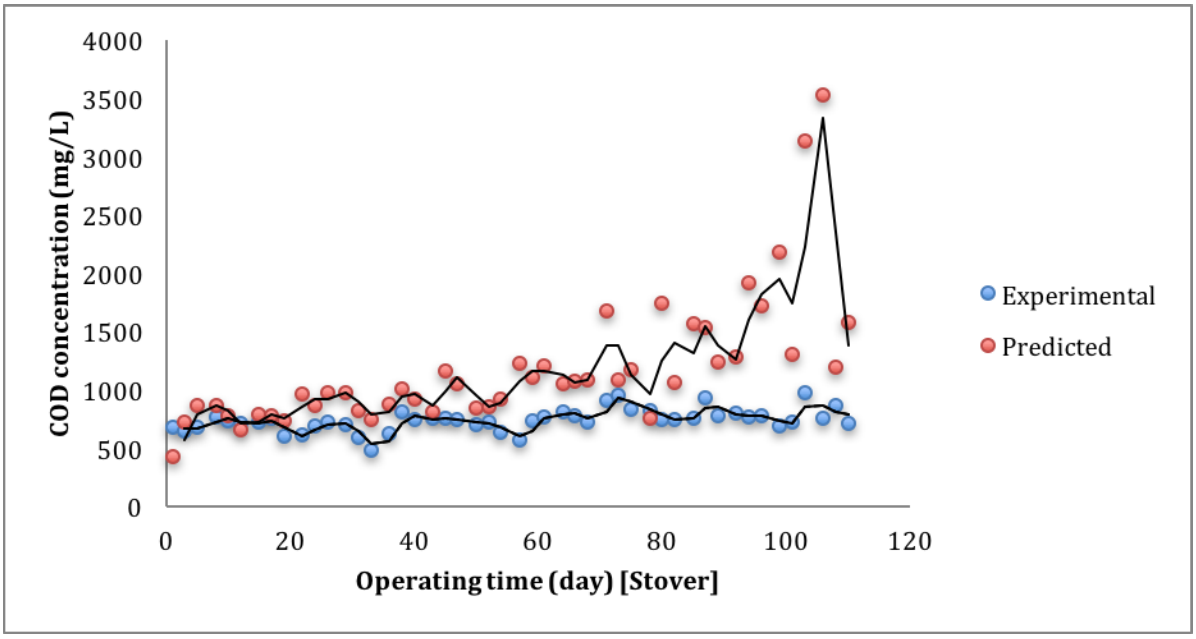

Figure 6.6: Modified Stover-Kincannon model application

Table 6.3 indicates kinetic coefficients U_{max} and K_B of the modified Stover-Kincannon obtained in this study in comparison with other studies with different substrates and reactors at mesophilic conditions. As seen from Table 6.3, the value of U_{max} and K_B obtained from this study were lower than those observed from other studies conducted using the SGBR treating both meat and poultry slaughterhouse wastewater.

Table 6.3: Comparison of the kinetic coefficient in the modified Stover-Kincannon model

Feed Substrates	Type of reactor	U_{max} (gCOD/L.day)	K_B (gCOD/L.day)	R^2	References
Poultry Slaughterhouse	SGBR	12.70	18.2	0.95	**This study**
Meat slaughterhouse	SGBR	192.3	206.6	0.99	(Oh, 2012)
Poultry slaughterhouse	SGBR	164.48	177.21	0.99	(Debik, 2009)
Textile wastewater	Hybrid column Up-flow anaerobic fixed bed reactor	31.69	45.37	0.99	(Sandhya & Swaminathan, 2006)
Simulated Textile wastewater	Up-flow anaerobic sludge bed reactor	7.5	8.2	0.99	Isik &Sponza, 2005
Paper Mill wastewater	Anaerobic Filter	86.21	104.15	0.99	(Yilmaz *et al*., 2008)

6.6Summary

Poultry slaughterhouses consume a substantial quantity of potable water during the processing of live birds. Subsequently, high strength poultry slaughterhouse wastewater (PSW) is generated at different stages during poultry product processing. In this study, a Static Granular Bed Reactor (SGBR) was used to treat the PSW from a poultry product processing facility in the Western Cape, South Africa. The performance of the SGBR was primarily evaluated for chemical oxygen demand (tCOD) removal with the kinetics of the treatment process for PSW being evaluated using both the Grau second-order and the modified Stover-Kincannon models to predict the effluent COD (S_e). The overall treatment efficiency averaged > 80% when the SGBR was operated at steady state for the 110-day experimental trial. On the basis of the experimental results, the predicted values of the tCOD concentration using the Grau second-order and modified Stover-Kincannon model were inconsistent with the experimental data, indicating an insignificant correlation with predicted tCOD concentration being higher than the experimental data. The high variation between the modelled and experimental data based on both the Grau second-order and modified Stover-Kincannon model was observed at higher organic loading rates when the reactor was fed with undiluted influent, a phenomenon attributed to tCOD trapped inside the SGBR, especially during periods of clogging caused by the accumulation of suspended solids in the under-drain.

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CHAPTER SEVEN

SUMMARY AND CONCLUSIONS

7. SUMMARY AND CONCLUSIONS

7.1Summary

Two sets of experiments were conducted in this study: 1) with an up-flow EGSB reactor coupled to an anoxic-aerobic bioreactor system (Chapter Four); and 2) with a down-flow SGBR coupled to an UF membrane to evaluate a suitable configuration with a high performance for the treatment of poultry slaughterhouse wastewater in South Africa (Chapter Five). Furthermore, a re-run of the EGSB reactor based on an improved operational strategy was conducted with results being discussed in Appendix C. Similarly, the SGBR was also re-run at varying OLRs and HRTs, generating experimental data that was used for kinetic parameter quantification using both Grau second-order and modified Stover-Kincannon models in Chapter Six.

The EGSB reactor coupled with an anoxic-aerobic bioreactors system was operated over a short period of time (26 days) at an HRT of 7(168 hr), 4 (96 hr), 3 (72 hr) days at OLRs range of 0.5, 0.7 and 1 gCOD/L.day, while the down-flow SGBR coupled with a UF membrane as an alternative to the EGSB /anoxic-aerobic bioreactor system was operated at HRTs of 55 and 40 hrs with OLRs of 1.01 and 3.14 gCOD/L.day, respectively. The EGSB reactor with an improved operational strategy was operated for 105 days at HRTs of 55, 60 and 65 hr, with OLRs averaging 1.05 to 1.95 gCOD/L.day. Subsequently, the SGBR re-run was operated over a period of 110 days at HRTs of 55, 96, 48 and 36 hr and OLRs range of 0.623 to 7.806 gCOD/L.day.

During initial experiments, the brief operational period for the EGSB/aerobic-anaerobic bioreactor system was due to continuous reactor instability caused by periodic sludge-washout, in particular, at high organic loading rates. During these experiments, the average tCOD removal achieved was 65%, with the EGSB performance ranging from 40 to 55% at various OLRs. This culminated in the development of an alternative operational strategy, whereby the influent was pre-treated using a sieve screen and feeding PSW during the start-up at 50% dilution using process water, with the gradual reduction in dilution to 30% and finally undiluted PSW in order to minimise FOG facilitated flotation of anaerobic biomass and toxicant inhibition(see Appendix C). As a result, significant improvements were observed to the overall tCOD reduction even at low HRT of 55 hrs and a high OLR of 1.95 gCOD/L.day respectively. The quality characteristics of the treated effluent from the improved EGSB operation met the South African industrial discharge standards. However, the reclaimed treated water will require further post-treatment prior to re-use. To adequately address limitations in the EGSB, another design option was evaluated, the SGBR.

The down-flow configured SGBR, attached to a UF membrane system, showed greater potential than the EGSB, particularly when key indicators such as tCOD, TSS and FOG being removed at $\geq$ 90%. Utilizing the UF membrane system (i.e. as a sequential post-treatment system) was advantageous, with further reductions of 64%, 88% and 60% for tCOD, TSS and FOG, respectively. The down-flow SGBR configuration has demonstrated a suitable low cost and practicable PSW treatment system, with a higher reactor performance and low biomass washout. However, the accumulation of particulate matter in the reactor can render the system redundant when operated for elongated periods. Furthermore, the use of the post-treatment UF membrane system further improved the quality of the SGBR reclaimed water, an indication that the treated water can be used for other amenities in the slaughterhouse, thus reducing the intake of potable water, as is currently the case. Further operational challenges can be endemic at higher OLRs and low HRTs including the use of an inappropriate underdrain system. Periodic backwash to declog fine sludge particles from the underdrain was required to re-suspend anaerobic biomass for maximum organic matter/biomass contact longevity and to increase total surface area contact attributed to the fluidisation, the expansion of the sludge-bed, which culminated in the sloughing-off of dead biomass. The deactivated grey biomass was easily flocculated in such an operation, through the overflow line, analogous to a purge stream used in other process engineering designs.

Since process modelling can be used to predict performance outcomes, the SGBR kinetic parameters were quantified for the re-ran SGBR experiments for a system operated for 110 days at HRTs of 96 to 36 hr and averaged OLRs of 0.78 to 4.10 gCOD/L.day for predicting substrate removal rates from the PSW using the Grau second-order and modified Stover-Kincannon models. There was minimal correlation between the predicted and experimental data for both the Grau second-order and modified Stover-Kincannon models, with a high variation observed at higher OLRs of 4.10 gCOD/L.day when the SGBR influent was undiluted PSW. The variation between predicted and experimental data was hypothetically assumed to be influenced by head losses through the granular bed due to accumulated excess biomass and solids retained by the underdrain, a phenomenon unaccounted for by the models used. Overall, the SGBR sustained a high tCOD removal, 82%, despite these operational deficiencies and changes in OLRs including HRTs, an indication of the ability of the system to adapt, even under strenuous operational conditions, requiring a backwash system to fluidise the sludge-bed and periodically purge the system of fine particles and sloughed-off inactive biomass which was easier to flocculate out of the system

In terms of local SA conditions, with the majority of the operational plant personnel being semi-skilled, the down-flow SGBR proved to be a better alternative to the up-flow EGSB reactor in treating PSW, requiring minimal monitoring and operational interventions while still maintaining a high performance even at high OLRs, including low HRTs in comparison to the EGSB reactor, although the EGSB performance improved after the implementation of an improved operational strategy (Appendix C). Low performance outcomes were observed, achieving only 64% tCOD reduction at an average OLRs range between 1.05 to 1.95 gCOD/L.day for a system operated over a period of 105 day. Following comparative analysis, the SGBR (Chapter Five), was deemed an adequate option as higher OLRs (3.14 gCOD/L.day) culminated in higher tCOD reduction (93%), with further OLR increases to 4.10 gCOD/L.day (Chapter Six), slightly decreasing the SGBR tCOD removal to 82%.

7.2 Process engineering significance

The main advantage of the high-performance rate anaerobic digester is the benefit of its capability to treat medium-to-high strength wastewater at low sludge production rates, and the ability to generate biogas for sustainable energy requirements. The down-flow SGBR, unlike the up-flow EGSB reactor, has demonstrated a high-performance rate, an attribute suggested to be influenced by biomass retainment in the form of anaerobic granules; with the counter current-flow in the SGBR conferring advantageous attributes, this included a limited need for a gas-liquid-solids separation (GLSS) system.

7.3 Significant contributions from this study

- Currently there is no published data on PSW in SA, although an increase in slaughterhouses was observed in the last decade (2008 to 2017). This study offers an insight to the situational analysis in South Africa with regard to slaughterhouse water usage and to propose treatment methods while highlighting their limitations when treating PSW.
- The study also explored possible post-treatment methods (such as use of UF membrane) that could be employed by the slaughterhouses in efforts to conserve and mitigate the need for fresh water resources.
- As of October 2017, the City of Cape Town has implemented a water rationing scheme, highlighting the urgency for this present research undertaken.

7.4Future studies and this study limitations

This study was conducted under conditions of university student unrest at South African universities (2015 and 2016) resulting in reduced reactor operation times deemed unsatisfactory, culminating in a re-run of both the SGBR and EGSB experiments to gather sufficient data to for adequately assessing reactor performance of both the up-flow EGSB and down-flow SGBR AD for the treatment of the poultry slaughterhouse wastewater. Biogas was collected although difficulties were encountered with measuring equipment, generating inconsistent results not reported in this thesis. An investment in a reliable gas measuring equipment can produce additional information on the suitability of each reactor as biogas plays an important role in reducing operating costs when used as an energy source to maintain system energy/heat requirements. Furthermore, the recovery of micro-nutrients such as phosphorous, including proteins from the poultry slaughterhouse wastewater, could be investigated as part of a future study.

A study on the improvement of the design in order to treat and re-use treated process wastewater, and also to achieve minimal discharge to the municipal sewer system, would thus be beneficial to minimise potable water consumption in poultry slaughterhouses. A proposed design and system reconfiguration could include a single stage simultaneous nitrification and aerobic denitrification process with a side stream membrane bioreactor. Due to the use of pharmaceutical active compounds

(PhACs) in the poultry industry, a study on the identification, quantification and fate of these PhACs for poultry slaughterhouse wastewater must be conducted in future studies, as PhACs pose an environmental health risk as they have a potential to promote or maintain bacterial resistance and disrupt key metabolic processes that are critical to biota. They are used in poultry farming as antimicrobials to minimise disease and infection outbreaks associated with fungal infestations, including parasites, with some being steroids (hormones) to promote bird growth.

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CHAPTER NINE

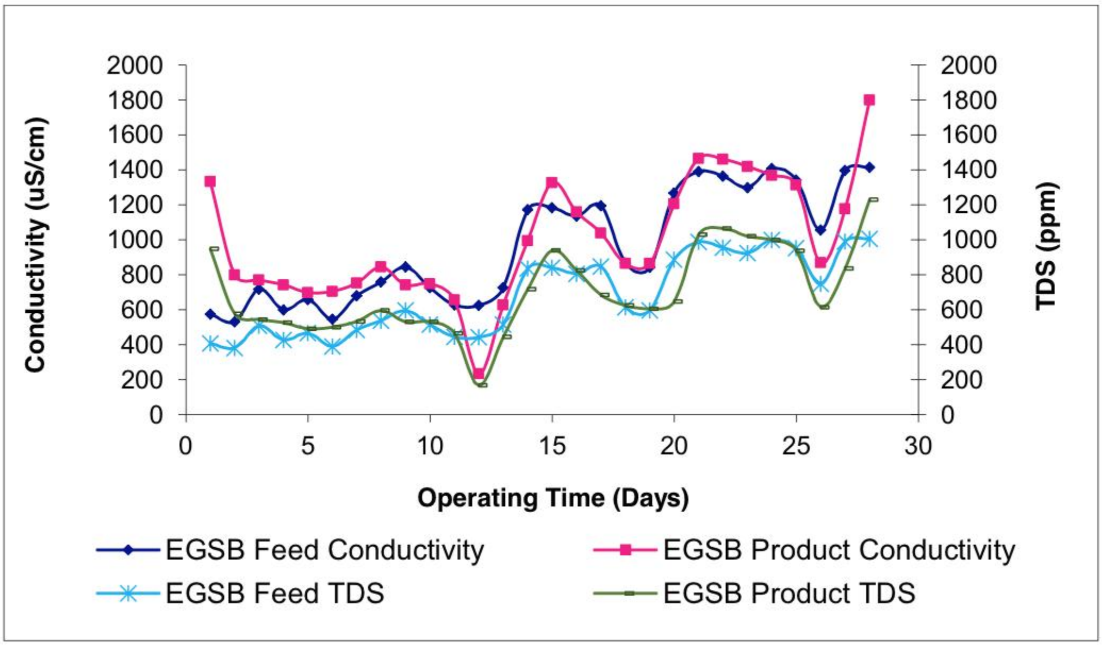
APPENDICES

A. APPENDICES

APPENDIX A: ADDITIONAL DATA FOR EGSB-ANOXIC AND AEROBIC BIOREACTOR SYSTEM (CHAPTER FOUR)

Conductivity and TDS

The electrical conductivity (EC) and total dissolved solids (TDS) of the raw EGSB feed, EGSB product, anoxic tank and aerobic tank was monitored throughout the operation, as shown in Figure A1. The conductivity of the raw poultry wastewater (EGSB feed) was 500 to1200 μS/cm, with effluent having 200 to 1798 μS/cm. The TDS for the raw wastewater feed ranged from 300 to 800 mg/L during the operation. Variations in the conductivity, including TDS, was due to influent quality changes, as the wastewater was industrial and not synthetic. Both the conductivity and TDS of the aerobic tank were less than those observed for the anoxic tank, which was attributed to microorganisms in the bioreactors being able to use or absorb some of the ions resulting in reduced conductivity as observed from the EGSB product, aerobic and anoxic reactor system. Overall, the conductivity and TDS values of the aerobic product were within the South African industrial wastewater discharge standards.



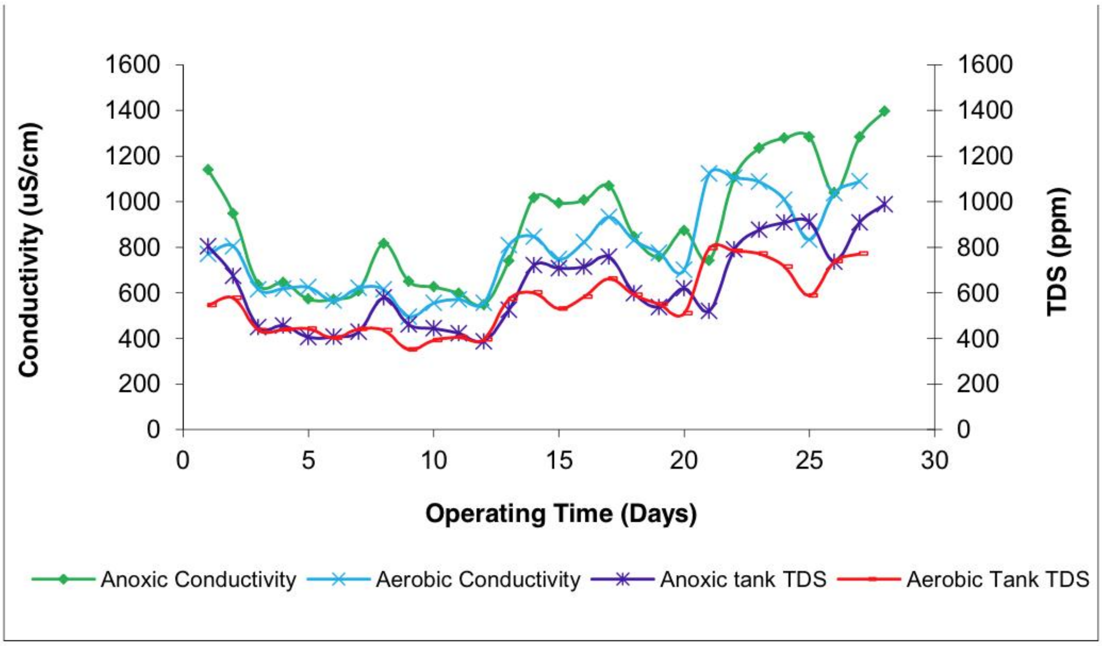


Figure A.1: Conductivity vs TDS of the EGSB, anoxic and aerobic bioreactor

B. APPENDIX B: ADDITIONAL DATA FOR SGBR AND UF OPERATION IN CHAPTER FIVE

The SGBR coupled with UF membrane system was operated at different HRTs and OLRs (see Figure B1) At a HRT of 55 hrs, while maintaining an average OLR of 1.01 g COD/L.day for 44 days, the tCOD reduction was > 95%. For the first 19 days, the SGBR was fed with 50% diluted PSW, with dilution being reduced 33% (2:1) at 20 to 28 days, subsequent to the use of undiluted PSW for a further 16 days at an HRT of 55 hr. The HRT was thereafter reduced to 40 hrs for the remainder of the experiments (last 21 days) at an average OLR of 3.14 g COD/L.day, which was observed to have conferred minimal operational limitations.

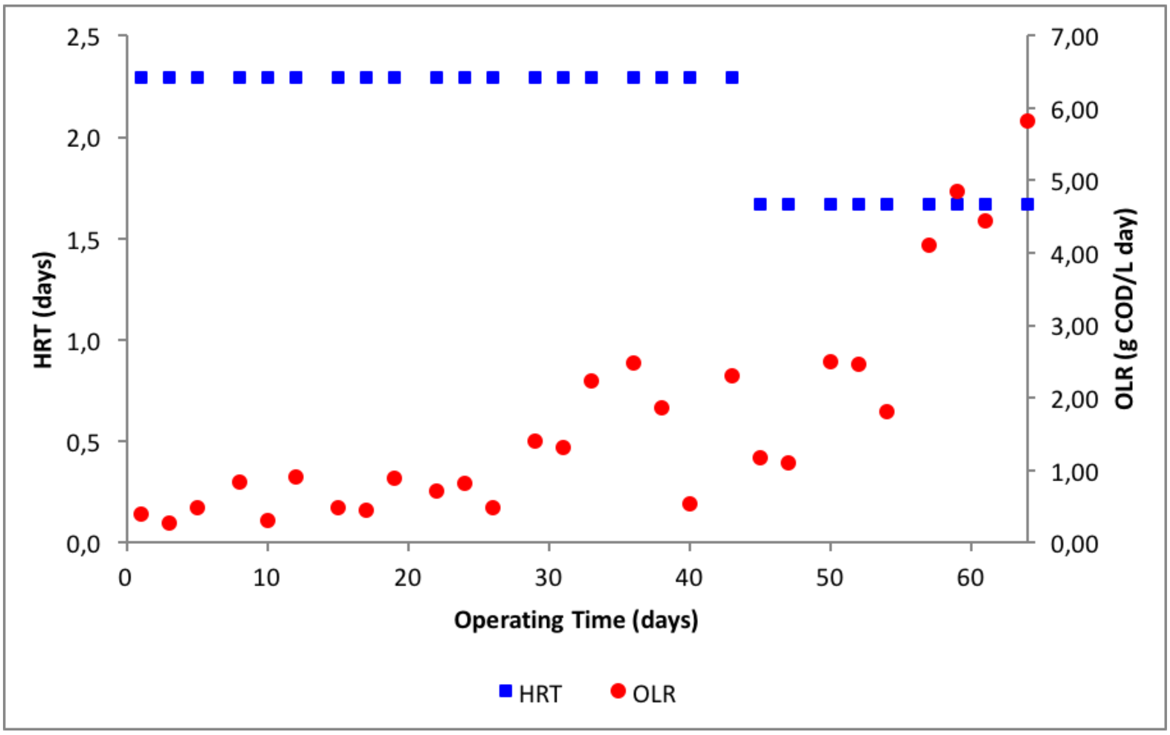


Figure B.1: Variations of HRT and OLR

Variation of Temperature and pH

The pH of the PSW is also influenced by chemicals used during the cleaning and sanitizing stages of bird processing. According to Gerardi (2003), the optimum pH for acceptable activity of methane-forming microorganisms and methane production under mesophilic conditions (35-40˚C) is at pH 6.8 to 7.2 with pH values in this range facilitating adequate alkalinity to minimize the impact of organic acids produced during organic matter conversion in the SGBR anaerobic biomass bed. For the duration of this study, the operating temperature of the SGBR was maintained by circulating water from a thermostatic bath through the heating jacket surrounding the SGBR. Figure B2 represents the pH profile of the primary system used as a function of temperature.

The range of pH maintained, 6.31 and 7.28, and an average of 6.83, is typical of poultry slaughterhouse wastewater as observed by Debik (2009), De Nardi *et al*. (2007) and Del Nery (2007) reported pH ranges of 5.6-8.1, 6.3-7.0 and 6.5-7.0, respectively, for high rate anaerobic digesters treating poultry slaughterhouse wastewater, although the pH of the SGBR effluent was at a slightly higher range of 6.42 to 7.97, averaging 7.46. Inhibitory factors for anaerobic digesters for the SGBR were attributed to insufficient heating and maintenance of optimum digester temperature (i.e. mesophilic conditions, which may have resulted in minute accumulation of caustic constituents and thus the slight increases in pH values outside the optimum range). Ultimately, this may have affected the stability and performance of the SGBR system since the microorganisms involved in the anaerobic digestion process respond differently at different temperatures.

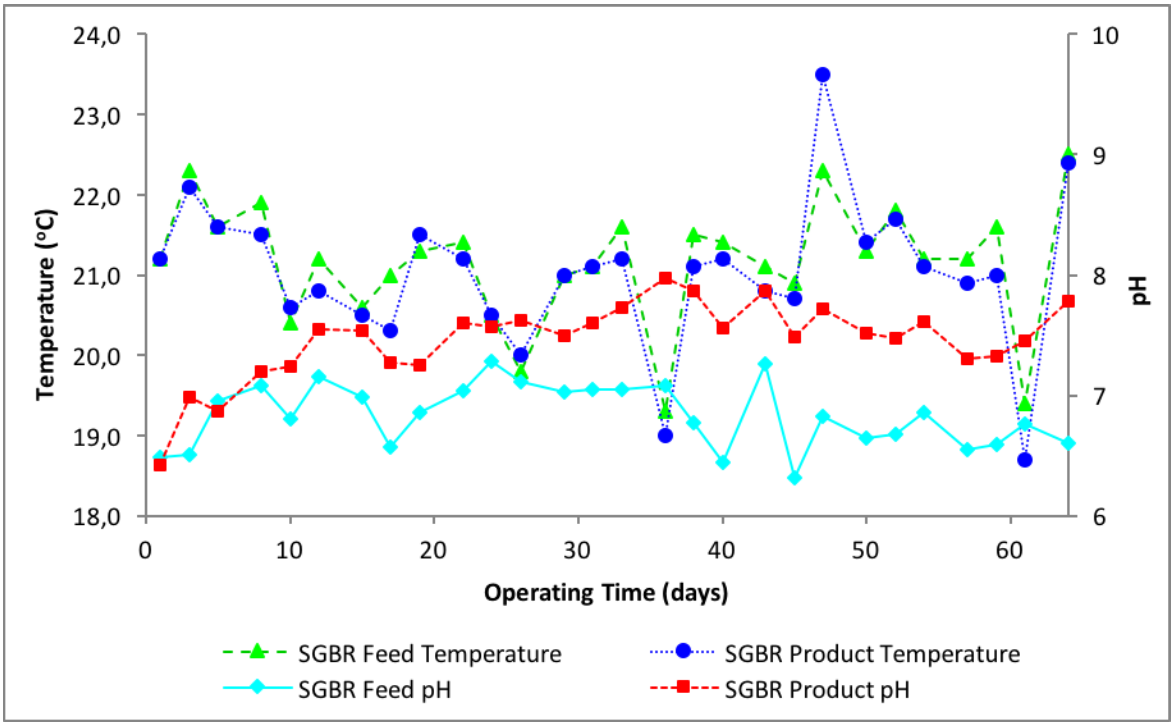


Figure B.2: Variation in pH and temperature

VFA and Alkalinity ratio

According to the analyses of the SGBR effluent, the VFA concentrations was 13 to 78 mg/L with the alkalinity between 572 and 979 mg/L. The alkalinity and VFA are inversely proportional; hence, the VFA concentration decreased as the alkalinity increased. Alkalinity of the anaerobic biomass can self-regulate, with biomass constituent maintaining the pH of the system for regulating the accumulation of volatile acids. The stable pH values observed and the decrease in VFA suggested that the SGBR system was relatively stable throughout this study, although at slightly lower temperature than that required. As the VFA/alkalinity ratio serves as an indication of the stability of the SGBR system, Oh *et al*. (2014) indicated that this ratio should be less than 0.3 to indicate process stability. With the ratio obtained for the average VFA and alkalinity, at 39 mg/L and 803 mg/L, respectively, the VFA/alkalinity was found to be 0.05, a value below the 0.3 maximum required indicating adequate operation of the SGBR.

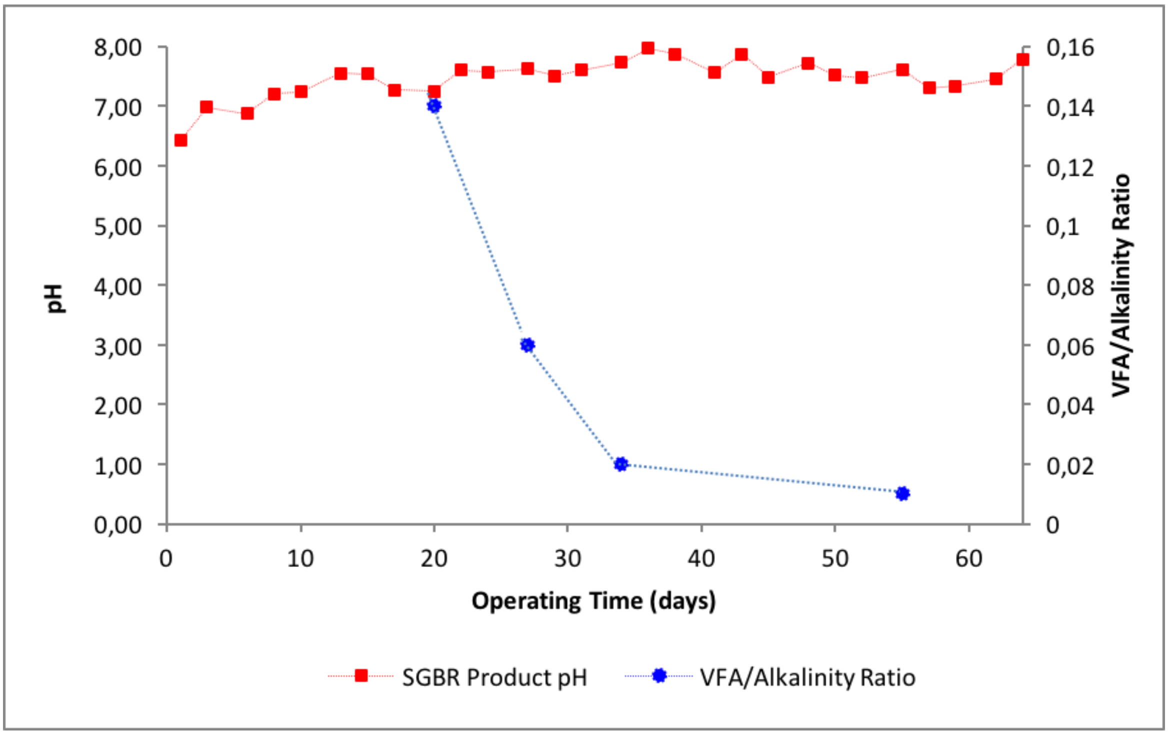


Figure B.3: Variation of pH and VFA/alkalinity ratio

Variation of TSS and Turbidity

Figure B4 illustrates the variation between the TSS and the turbidity. The TSS was quantified to determine the concentration of insoluble organic and inorganic particles suspended in the PSW; the turbidity was determined as relative clarity of the wastewater, an indication of the extent to which solid particles obstruct the transmittance of light through the wastewater. Despite TSS and turbidity being related, turbidity is not a direct measurement of the suspended particles present in the wastewater. It can be seen from Figure B4 that the TSS and turbidity of the SGBR feed varied substantially throughout the study because of the variation in the SGBR feed. The TSS and turbidity of the SGBR effluent, however, remained relatively stable and followed a similar profile, with variations influenced by changes in either HRT or OLRs. It is evident from Figure B4 that the SGBR successfully reduced the TSS and turbidity content of the poultry slaughterhouse wastewater. The TSS of the SGBR feed ranged between 734 and 4992 mg/L, whereas the TSS of the SGBR product ranged between 20 to 320 mg/L. The average TSS treatment efficiency obtained in this part of the study was 94.8%, further verifying the entrapment of suspended solids by the SGBR. Similarly, the turbidity of the SGBR feed varied between 72.60 and 841 NTU with an average turbidity of 482 NTU. The SGBR product turbidity was at a low 9.06 and 225 NTU averaged 60.4 NTU.

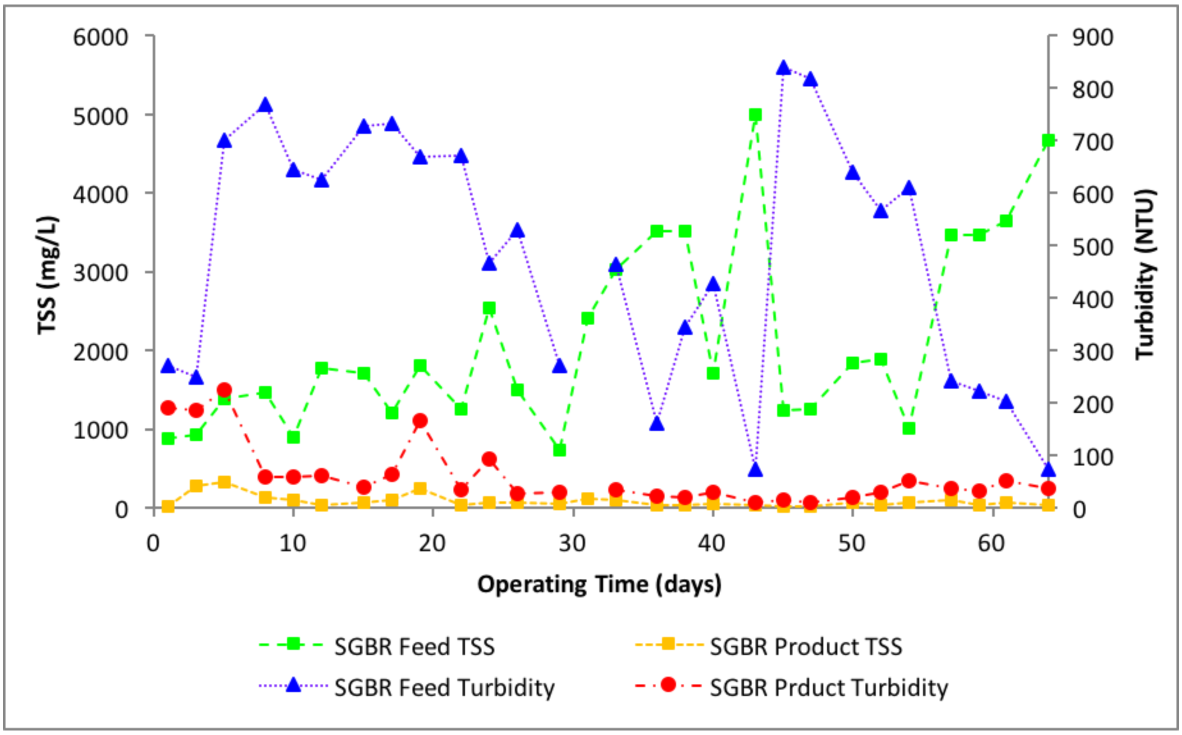


Figure B.4 : Variation in TSS and turbidity

Variation in TDS, conductivity and salinity

The relationship between the TDS and conductivity is interrelated as the TDS quantifies of concentration of soluble organic and inorganic matter present in the poultry slaughterhouse wastewater, with conductivity measured to determine the ability of the wastewater to conduct an electrical charge. Theoretically, an increase in the number of dissolved solids would thus have a direct influence on the conductivity.

Due to operational variation, the TDS of the SGBR product fluctuated throughout the study (Figure B5) with values of 680 to 1360 mg/L and an average of 1085 mg/L. At certain time intervals, the TDS of the SGBR product increased, specifically to 743 to 1020 mg/L at days 1 to 3, from 697 to 970 mg/L for days 12 to 15, from 680 to 1090 mg/L at days 17 to 22, 1020 to 1360 at days 24 to 33, 1050 to 1320 mg/L at days 36 to 40, and from 1160 to 1300 mg/L for days 45 to 54. This distribution of the dissolved solids suggested that it was necessary to use physical separation technology in the form of a UF membrane system to reduce the TDS and thereby reduce the treated wastewater conductivity.

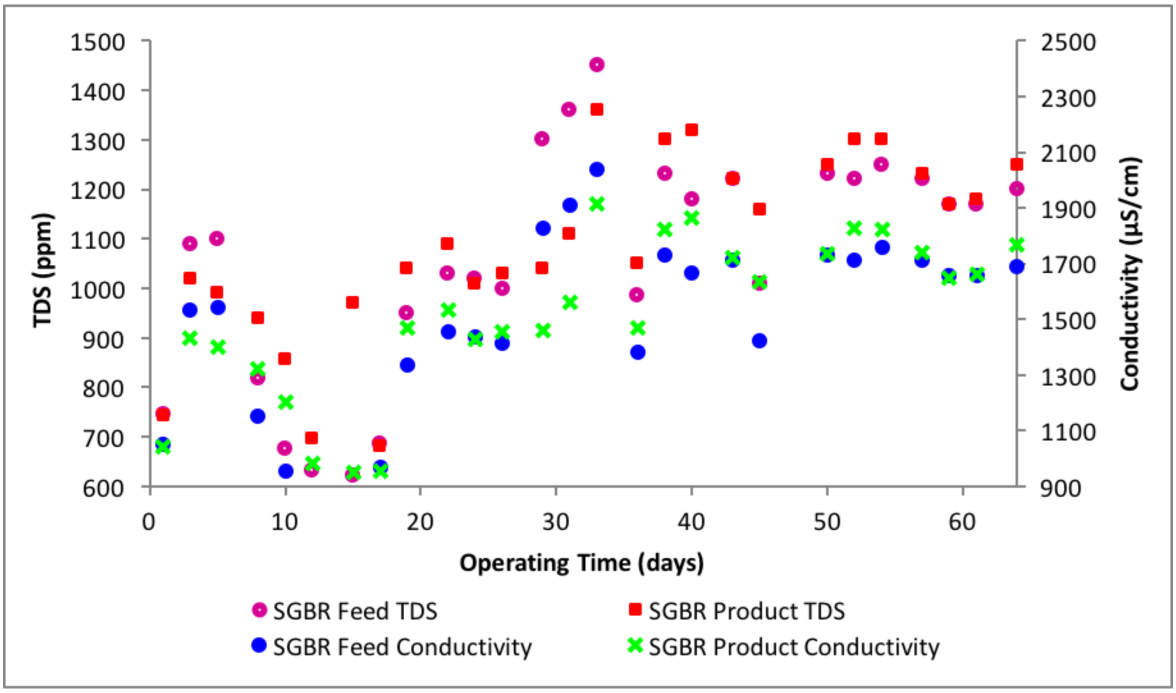


Figure B.5: Relationship between TDS and conductivity

Furthermore, a comparative analysis of salinity influence on conductivity was done, as illustrated in Figure B6, showing the relationship between the salinity and TDS of the SGBR feed and product since the two parameters are interrelated. The salinity of the SGBR feed ranged between 485 and 1240 mg/L with an average of 801 mg/L with observations made that an increase in salinity quantified as TDS resulted in redissolved solids due temporary increases in temperature which influences the equilibrium de- and absorption of dissolved from the biomass. The salinity of the SGBR product increased from 547 to 1010 mg/L, with an average salinity of 793 mg/L.

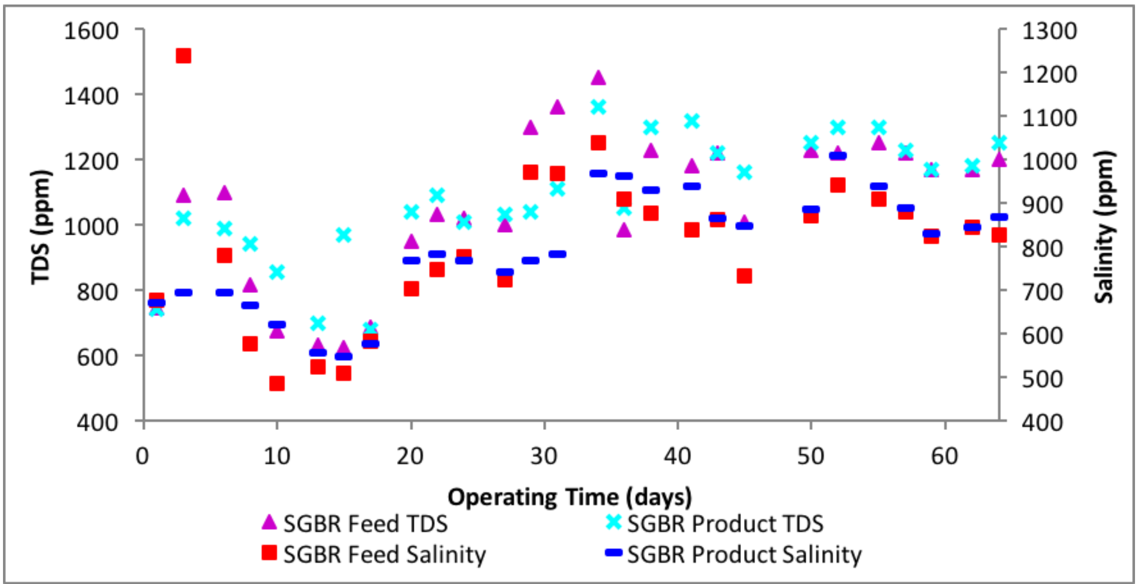


Figure B.6: Relationship between conductivity and salinity

Overall treatment efficiency of the combined SGBR and UF membrane system

The tCOD was used to evaluate the performance and overall effectiveness of the SGBR system throughout this study. From Figure B7, it is evident that the average tCOD concentration of the poultry slaughterhouse wastewater obtained from the industrial partner *did not* meet the maximum limit of permitted discharge for tCOD (5000 mg/L) according to the CCT wastewater and industrial effluent by-law (2013). Following the anaerobic pre-treatment in the SGBR, the tCOD concentration was significantly reduced with an average tCOD removal of 93.1% over the 64 day period of this study. As a result, the pre-treated poultry slaughterhouse wastewater used as feed for the UF membrane contained a minimum tCOD concentration of 15 mg/L and an average of 244 mg/L, significantly lower than the SGBR feed. The treatment efficiency remained consistent throughout the experiments at >90% which corresponded to previous studies reported by Evans (2004). The TSS concentration in the poultry slaughterhouse wastewater was also used to quantify the performance of the SGBR with the average treatment efficiency for the removal of total suspended solids being 94.8%.

Using TDS and conductivity, it is evident that post-treatment was indeed required to meet the discharge limits. Despite the variation in the poultry slaughterhouse wastewater, the SGBR system produced consistent results, meeting required discharge standards.

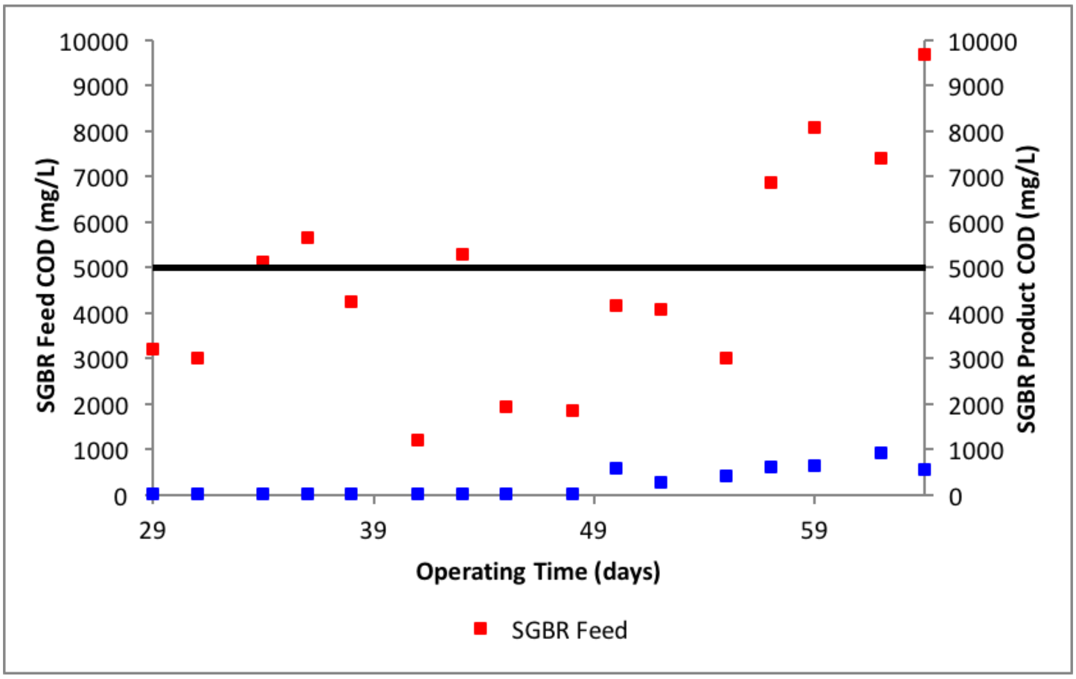


Figure B.7: Overall treatment efficiency of the combined SGBR-UF system

C. APPENDIX C: IMPROVED OPERATIONAL STRATEGY OF THE EGSB REACTOR

Motivation for an improved operational strategy

As reported in Chapter Four, a low overall tCOD removal of 51% was achieved when treating PSW using an EGSB reactor over a period of 26 days. The inadequate reactor performance in terms of tCOD removal was attributed to periodic sludge washout and a high concentration of FOG in the influent used resulting in system failure. Furthermore, the system required continuous re-inoculation due to a loss of active granules. Therefore, an improved operation strategy involving reduction of the FOG in the influent and suspended solids by filtration, using it using a 2mm mess sieve, with the influent diluted during the acclimatization period prior to the introduction undiluted PSW, were deemed sufficient to reduce sludge wash-out. Thus, it could be hypothesized to improve the EGSB performance efficiency which needed to be evaluated.

Material and methods

The cylindrical glass EGSB reactor, with an inner diameter of 0,065 m and height of 0,872 m and working volume of 2.33 L, was used on the improved operation strategy. The reactor was packed with 0.5 m diameter of ceramic marble at the bottom to assist with the influent distribution to avoid channelling. A Gilson multi-head pump was used for pumping the influent into the EGSB reactor. The influent was diluted at 50% (v/v), 30% dilution and then undiluted PSW was sequentially fed, as shown in Table C1. The EGSB reactor was maintained under mesophilic conditions using a thermostatic water bath, with the warm water continuously circulated. The influent was filtered (2mm mesh sieve size) to remove feathers, suspended solids and FOG. The EGSB bioreactor was operated at HRTs of 55 hr, 60 hr and 65 hr corresponding to OLRs of 1.05, 1.93 and 1.95 gCOD/L.day, respectively, over a period of 95 days.

Table C.1: EGSB operating conditions

Dilution (%)	Days	HRT (hrs)	OLR (g COD/L.day)
50%	42 days	55	1.05
30%	32 days	60	1.93
No dilution	21 days	65	1.95

Results and discussions

Performance of the EGSB reactor based on improved operation strategy

Table C2 summarizes tCOD, TSS and FOG percentage removal rates under various organic and hydraulic loading conditions. During the start-up period, using a dilution of 50%, the average tCOD, TSS and FOG removal rate was 46%, 78% and 89%, respectively, at an initial OLR of 1.05 gCOD/L.day and a HRT of 55 hr (2.29 days). Furthermore, at a 30% dilution, the average tCOD, TSS and FOG removal rate was 65%, 91% and 80%, respectively at OLR of 1.93 gCOD/L.day and a HRT of 60 hr (2.5 day). Subsequent to the introduction of undiluted PSW influent, the average tCOD, TSS and FOG removal was 81%, 88% and 86%, respectively, at OLR of 1.95 gCOD/L.day and HRT of 65 hr (2.7 days). Furthermore, a significant improved tCOD removal was observed, possibly due to stabilization of the EGSB system.

Table C.2: Performance of the EGSB based on improved operation strategy treating PSW

Dilution	Day	HRT (hr)	OLR(gCOD/L.day)	COD removal (%)	TSS removal (%)	FOG (%)
50%	1-42	55	1.05	46 ± 6	78 ± 6	89 ± 0.9
30%	42-74	60	1.93	65 ± 7	91 ± 2	80 ± 3.0
100% PSW	74-105	65	1.95	81 ± 4	88 ± 3	86 ± 0.2

Overall COD, TSS and FOG removal for EGSB in comparison to SGBR study in Chapter Five

Table A1 illustrates the overall tCOD, TSS and FOG removal from the adopted improved operation strategy for the EGSB reactor in comparison with the SGBR study in Chapter Five. The overall tCOD, TSS and FOG removal of the EGSB system was found to 65%, 71% and 83% respectively. Comparing the overall performance in terms of tCOD, TSS and FOG of the EGSB and the SGBR study in Chapter Five; the results indicate a better performance for the SGBR, as shown in Table C3.

Table C.3: Summary of results of EGSB and SGBR

Parameter	EGSB reactor	SGBR
COD (%)	64	93
TSS (%)	86	95
FOG (%)	85	90

Summary

While both EGSB and SGBR were able to treat the PSW, both faced different operational challenges such as sludge washout for the EGSB reactor and clogging of the under-drain pea gravel for the SGBR, which has a potential to affect the overall performance of the reactor. Despite these challenges, in particular the clogging of the under-drain that requires a regular backwash, the overall SGBR system performance was higher and consistent as compared to the EGSB operated with the new operation strategy. Therefore, the down-flow SGBR was deemed the most viable reactor configuration to treat PSW with high TSS and FOG content, when compared to EGSB.

APPENDIX D: MODELLING DATA FOR CHAPTER SIX

Table D.1: Modified Stover-Kincannon modelling data

Q(L/day)	OLR(gCOD/L)	HRT (days)	HRT (hr)	**time**	**Si(gCOD/L)**	**S0(mg/L)**	**V/(Q(S0-Se)**	**1/OLRs**	**Umax*S0**	**KB+(QS0/V)**	**Se (predicted)**	**COD%**
0,87	0,623	2,29	55	1	1,43	676	3,0515	1,61	18059	18101,89	429	53
0,87	1,041	2,29	55	3	2,39	650	1,3196	0,96	30211	18102,31	718	73
0,87	1,247	2,29	55	5	2,86	676	1,0507	0,80	36160	18102,51	859	76
0,87	1,257	2,29	55	8	2,88	768	1,0844	0,80	36477	18102,52	867	73
0,87	1,120	2,29	55	10	2,57	731	1,2482	0,89	32489	18102,39	772	72
0,87	0,958	2,29	55	12	2,20	709	1,5417	1,04	27785	18102,22	660	68
0,87	1,147	2,29	55	15	2,63	717	1,1988	0,87	33270	18102,41	790	73
0,87	1,124	2,29	55	17	2,58	751	1,2552	0,89	32616	18102,39	775	71
0,87	1,058	2,29	55	19	2,43	596	1,2530	0,95	30696	18102,32	729	75
0,87	1,404	2,29	55	22	3,22	616	0,8811	0,71	40717	18102,67	967	81
0,87	1,255	2,29	55	24	2,88	690	1,0480	0,80	36414	18102,52	865	76
0,87	1,409	2,29	55	26	3,23	717	0,9120	0,71	40886	18102,68	971	78
0,50	0,810	4,00	96	29	3,24	699	1,5742	1,23	41013	18102,08	974	78
0,50	0,682	4,00	96	31	2,73	590	1,8709	1,47	34536	18101,95	820	78
0,50	0,623	4,00	96	33	2,49	482	1,9920	1,61	31519	18101,89	749	81
0,50	0,725	4,00	96	36	2,90	624	1,7577	1,38	36709	18101,99	872	78
0,50	0,833	4,00	96	38	3,33	805	1,5831	1,20	42173	18102,10	1002	76
0,50	0,763	4,00	96	40	3,05	740	1,7316	1,31	38608	18102,03	917	76
0,50	0,678	4,00	96	43	2,71	750	2,0408	1,48	34304	18101,94	815	72
0,50	0,965	4,00	96	45	3,86	753	1,2882	1,04	48840	18102,23	1160	80
0,50	0,878	4,00	96	47	3,51	742	1,4444	1,14	44451	18102,14	1056	79
0,50	0,700	4,00	96	50	2,80	705	1,9081	1,43	35464	18101,97	843	75
0,50	0,714	4,00	96	52	2,86	724	1,8766	1,40	36139	18101,98	859	75

0,50	0,768	4,00	96	54	3,07	636	1,6432	1,30	38861	18102,03	923	79
0,50	1,023	4,00	96	57	4,09	564	1,1345	0,98	51772	18102,29	1230	86
1,00	1,831	2,00	48	59	3,66	734	0,6832	0,55	46350	18103,10	1101	80
1,00	2,010	2,00	48	61	4,02	768	0,6151	0,50	50886	18103,28	1209	81
1,00	1,745	2,00	48	64	3,49	807	0,7454	0,57	44177	18103,01	1050	77
1,00	1,780	2,00	48	66	3,56	780	0,7193	0,56	45063	18103,05	1071	78
1,00	1,807	2,00	48	68	3,61	720	0,6913	0,55	45738	18103,07	1087	80
1,00	2,792	2,00	48	71	5,58	904	0,4274	0,36	70675	18104,06	1680	84
1,00	1,803	2,00	48	73	3,61	952	0,7538	0,55	45633	18103,07	1084	74
1,00	1,948	2,00	48	75	3,90	833	0,6528	0,51	49325	18103,21	1172	79
1,00	1,258	2,00	48	78	2,52	825	1,1825	0,79	31857	18102,52	757	67
1,00	2,898	2,00	48	80	5,80	746	0,3960	0,35	73376	18104,16	1744	87
1,00	1,769	2,00	48	82	3,54	748	0,7168	0,57	44789	18103,03	1064	79
1,33	3,469	1,50	36	85	5,20	760	0,3376	0,29	65865	18104,73	1565	85
1,33	3,387	1,50	36	87	5,08	931	0,3615	0,30	64304	18104,65	1528	82
1,33	2,744	1,50	36	89	4,12	780	0,4496	0,36	52110	18104,01	1238	81
1,33	2,850	1,50	36	92	4,28	794	0,4310	0,35	54114	18104,12	1286	81
1,33	4,256	1,50	36	94	6,38	766	0,2670	0,23	80802	18105,52	1921	88
1,33	3,816	1,50	36	96	5,72	781	0,3035	0,26	72447	18105,08	1722	86
1,33	4,836	1,50	36	99	7,25	692	0,2286	0,21	91814	18106,10	2182	90
1,33	2,892	1,50	36	101	4,34	726	0,4152	0,35	54916	18104,16	1305	83
1,33	6,951	1,50	36	103	10,43	974	0,1587	0,14	131983	18108,22	3138	91
1,33	7,806	1,50	36	106	11,71	755	0,1369	0,13	148207	18109,07	3524	94
1,33	2,643	1,50	36	108	3,97	869	0,4844	0,38	50190	18103,91	1193	78
1,33	3,493	1,50	36	110	5,24	713	0,3313	0,29	66329	18104,76	1576	86

Table D.2: Grau second-order modelling raw data

HRT (days)	HRT (hr)	**Time**	**Si**	**S0**	**E**	**HRT/E**	**SO(predicted)**
2,29	55	1	1427	676	0,53	4,35	367,6
2,29	55	3	2387	650	0,73	3,15	614,9
2,29	55	5	2857	676	0,76	3,00	736,0
2,29	55	8	2882	768	0,73	3,12	742,4
2,29	55	10	2567	731	0,72	3,20	661,3
2,29	55	12	2195	709	0,68	3,38	565,5
2,29	55	15	2628	717	0,73	3,15	677,2
2,29	55	17	2577	751	0,71	3,23	663,9
2,29	55	19	2425	596	0,75	3,04	624,8
2,29	55	22	3217	616	0,81	2,83	828,7
2,29	55	24	2877	690	0,76	3,01	741,1
2,29	55	26	3230	717	0,78	2,95	832,2
4,00	96	29	3240	699	0,78	5,10	813,9
4,00	96	31	2728	590	0,78	5,10	685,4
4,00	96	33	2490	482	0,81	4,96	625,5
4,00	96	36	2900	624	0,78	5,10	728,5
4,00	96	38	3332	805	0,76	5,27	837,0
4,00	96	40	3050	740	0,76	5,28	766,2
4,00	96	43	2710	750	0,72	5,53	680,8
4,00	96	45	3858	753	0,80	4,97	969,3
4,00	96	47	3512	742	0,79	5,07	882,2
4,00	96	50	2802	705	0,75	5,35	703,8
4,00	96	52	2855	724	0,75	5,36	717,2
4,00	96	54	3070	636	0,79	5,04	771,2
4,00	96	57	4090	564	0,86	4,64	1027,5

2,00	48	59	3662	734	0,80	2,50	951,3
2,00	48	61	4020	768	0,81	2,47	1044,4
2,00	48	64	3490	807	0,77	2,60	906,7
2,00	48	66	3560	780	0,78	2,56	924,9
2,00	48	68	3613	720	0,80	2,50	938,8
2,00	48	71	5583	904	0,84	2,39	1450,6
2,00	48	73	3605	952	0,74	2,72	936,6
2,00	48	75	3897	833	0,79	2,54	1012,4
2,00	48	78	2517	825	0,67	2,98	653,8
2,00	48	80	5797	746	0,87	2,30	1506,0
2,00	48	82	3538	748	0,79	2,54	919,3
1,50	36	85	5203	760	0,85	1,76	1381,1
1,50	36	87	5080	931	0,82	1,84	1348,4
1,50	36	89	4117	780	0,81	1,85	1092,7
1,50	36	92	4275	794	0,81	1,84	1134,7
1,50	36	94	6383	766	0,88	1,70	1694,3
1,50	36	96	5723	781	0,86	1,74	1519,1
1,50	36	99	7253	692	0,90	1,66	1925,2
1,50	36	101	4338	726	0,83	1,80	1151,5
1,50	36	103	10427	974	0,91	1,65	2767,5
1,50	36	106	11708	755	0,94	1,60	3107,7
1,50	36	108	3965	869	0,78	1,92	1052,4
1,50	36	110	5240	713	0,86	1,74	1390,8