PROCESS SIMULATION FOR A SMALL-SCALE POULTRY SLAUGHTERHOUSE WASTEWATER TREATMENT PLANT

by

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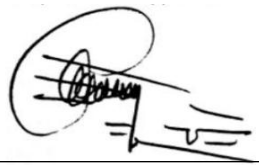
DECLARATION

I, **Lionnel Neddy Aymar NDEBA NGANONGO**, declare that the contents of this dissertation is my own unaided work, and which has not been submitted for academic examination towards any other qualification. Thus, it represents my own opinions and not necessarily those of the Cape Peninsula University of Technology and the National Research Foundation of South Africa.



01/11/2019

Signed **Date**

ABSTRACT

Fresh water is a renewable resource, but it is also finite, especially given environmental impacts from anthropogenic activities. Globally, there are countless signs that untreated industrial discharge into fresh watercourses is one of the main causes of ecosystem degradation. Poultry slaughterhouse wastewater (PSW) amongst the main pollutants of fresh water sources. In recent years, the world's pre-eminent researchers have developed innovative wastewater treatment processes to treat the large quantity of wastewater generated as well as to manage the environmental health concerns arising from PSW discharged into the environment. Furthermore, increasing wastewater treatment capital costs and the implementation of increasingly rigorous government legislation to mitigate environmental pollution whilst minimizing fresh water source contamination, requires that wastewater such as PSW, be adequately treated prior to discharge.

In order to assist the small-scale poultry producers in South Africa (SA), process simulation for a small-scale poultry slaughterhouse wastewater treatment plant was proposed using Sumo Wastewater treatment plant (WWTP) simulation software. Sumo is an innovative and most versatile wastewater simulation package on the market. The simulator is capable of modelling treatment plants of unlimited complexity, focusing largely on Biochemical oxygen demand (BOD), Chemical oxygen demand (COD), nitrogen and phosphorus removal; with digester, and side streams design options, being available. Considering the possible advantages in modelling and ongoing studies of implementing wastewater treatment to increase water management, anaerobic digestion of high strength wastewater such as PSW, warranted this research study. Model development from the simulation included the evaluation of numerous design options to assist small scale poultry producers, to have a variety of designs to choose from in their PSW WWTP designs.

With the aid of Sumo, two models were designed in this study, namely a single-stage and a two-stage anaerobic digestion without a recycle. The PSW used as feed was obtained from a local poultry slaughterhouse (Western Cape, South Africa). Both model designs predicted the reduction of the organic matter (COD, BOD_5) total suspended solids (TSS), and volatile suspended solids (VSS) in the PSW. The digester for the single stage anaerobic digestion system modelled was set to operate at steady state for 150 days under mesophilic temperature (35 ˚C) with a solid retention time (SRT) of 25 days. The COD, TSS, VSS and BOD removal efficiencies reached a maximum of 64%, 77%, 84%, and 94%, respectively, at an organic load rate (OLR) of 143.6 mg COD/L/day. A minute increase in the ammonia

(NH_3) and phosphate (PO^{3-}_4) concentration was observed once the simulation was completed.

As for the two-stage anaerobic digestion system, both digesters were set to perform at mesophilic temperatures (35 ˚C) and a SRT of 13 days in the first digester and 25 days in the subsequent digester. The two-stage anaerobic digestion showed better performance in comparison to the single-stage anaerobic digestion system. The COD, TSS, VSS and BOD_5 removal efficiencies reached a maximum of 69%, 79%, 85%, and 96%, respectively, at an at an OLR of 143.6 mg COD/L/day. A similar trend regarding phosphate and ammonia removal was noticed in the two-stage anaerobic digestion, suggesting a tertiary treatment system to be in place for further treatment.

Although, the two-stage anaerobic digestion demonstrated adequate performance, for the purpose of this study, the single-stage was the process recommended for PSW treatment, as it is less costly and will be suitable for small scale poultry producers; albeit biogas production is much higher when digesters are connected in series.

The PSW treatment modelling for this study was successfully employed with the resultant effluent being compliant with the City of Cape Town (CCT) wastewater and industrial effluent by-law discharge limits. Although, both the PO^{3-}_4 and NH_3 were suggested to require further monitoring.

Therefore, the poultry slaughterhouse from which the PSW was obtained will be able to safely discharge the treated wastewater proposed in this research into local water bodies, i.e. rivers in the Western Cape, SA; however, the treated PSW will not be suitable for re-use as process water.

Keywords: Anaerobic digestion, Anaerobic digestion model No.1 (ADM1), Activated sludge model No.1 (ASM1), Poultry slaughterhouse, Sumo, Wastewater treatment.

DEDICATION

This thesis is dedicated to my parents

Nestor NDEBA and Lydie Beatrice NGANONGO

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RESEARCH OUTPUTS

The scientific contribution emanating from the study was as follows:

- **Published DHET accredited conference proceeding(s):**

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LAYOUT OF THESIS

This thesis consists of the following 5 chapters:

- **Chapter 1** provides general background information of the South African poultry industry, poultry slaughterhouse wastewater (PSW) generation, and the treatment of PSW. It includes the research problem, questions, aim and objectives, including the significance and delineation of this study.
- **Chapter 2** is a literature review of the regulations governing the discharge of PSW in South Africa and the environmental impact and health effect associated with improper discharge of PSW. It contains a brief overview of anaerobic wastewater treatment process including the various technologies available for anaerobic PSW treatment.
- **Chapter 3** is a brief summary of the anaerobic digestion model No 1. It includes the model equations and discuss the relevancy of using Sumo as a simulation platform for WWTP.
- **Chapter 4** describes the materials, equipment and methods used for the PSW simulation process.
- **Chapter 5** presents the designs proposed for treating PSW and assess the results relating to the performance of the individual proposed model.
- **Chapter 6** provides the overall conclusions of this study with recommendations for further research.

All references used in this study are listed in accordance with the guidelines for research theses for a CPUT master's qualification.

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LIST OF ABBREVIATIONS

Abbreviation	Definition
AD	Anaerobic digestion
ADM	Anaerobic digestion model
AS	Activated sludge
ASM	Anaerobic sludge model
BOD_5	Biochemical oxygen demand
CCT	City of Cape Town
CH_4	Methane
COD	Chemical oxygen demand
DWA(SA)	Department of water affairs (South Africa)
EGSB	Expanded granular sludge bed
N	Nitrogen
NH_3	Ammonia
NH_4^+	Ammonium
NH_4^+-N	Ammonium-nitrogen
NO_3^-	Nitrate
NO_3^-N	Nitrate nitrogen
NO_2^-	Nitrite
NO_2^-N	Nitrite nitrogen
OLR	Organic loading rate
P	Phosphorous
PSW	Poultry slaughterhouse wastewater
SANAS	South African Nation Accreditation System
SANS	South African National Standard
SBR	Sequencing batch reactor
SGBR	Static granular bed reactor
SRT	Solids retention time
TDS	Total dissolved solids
TKN	Total Kjeldahl nitrogen
TOC	Total organic carbon
TSS	Total suspended solids
TN	Total nitrogen
UASB	Up-flow anaerobic sludge blanket
VFA	Volatile fatty acids

VSS	Volatile suspended solids
WDCS	Waste Discharge Charge System
WWTP	Wastewater treatment plant

GLOSSARY

Term	Definition/explanation
Anaerobic digestion	Biological process increasingly recognized for the pretreatment of high-strength wastewaters that are typical of many food producing industrial facilities (Seghezzo et al., 1998).
Bioremediation	Branch of environmental engineering which focuses on the eradication of toxins, pollutants, contaminants from soil and water using microorganisms i.e. microbes and bacteria (Boopathy, 2000).
High rate anaerobic digesters	Digesters capable of treating wastewater containing a high load of organic matter as well as able the retain biogas for use as a fairly clean energy source (Igoni et al., 2008).
Mathematical modelling	Description of a system using mathematical concepts and language.
Organic load rate (OLR)	Organic load rate (OLR) is the frequency upon which organic matter enters the reactor (Judd, 2010).
Poultry slaughterhouse	Facility where birds are killed for consumption as food (Canencia et al., 2016)
Solids retention time (SRT)	Solids retention time (SRT) is the timeframe in which biomass/solids are retained in the reactor (Judd, 2010).
Total suspended solids (TSS)	A percentage of the particles remain on a filter paper, which is determined once dried at 105 °C (Metcalf & Eddy, 2003).

CHAPTER 1
INTRODUCTION

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INTRODUCTION

1.1. Background

Fresh water is a renewable resource, but it is also finite, especially given environmental impacts from anthropogenic activities. Globally, there are countless signs that untreated industrial discharge into the watercourse is one of the main causes of ecosystem degradation. Poultry slaughterhouse wastewater (PSW) was identified is one of the culprits (Goel, 2006). According to Von Sperling (2017), PW plants generate a considerable volume of wastewater. Approximately 8 to 15 Litters per bird slaughtered (200-700m^3/day), as per their production target. These plants are commonly known as high strength wastewater producers, because of the characteristics of the wastewater they generate. The wastewater that comes from poultry slaughterhouse carries high concentrations of COD, suspended solids, oil, grease, nitrogen and phosphate (Coskun et al., 2016). The presence of these constituents are directly linked to the high organic matter from fat, blood from the bird's skin including protein from debris and oil from the boiling of birds for the removal feathers. As for nitrogen and phosphate, its source is faeces and urine from the animals slaughtered including sanitizing/cleaning products.

Researchers have spent tremendous efforts to develop innovative technologies and bioreactors to treat slaughterhouse wastewater to reach the acceptable discharge requirements. Such bioreactors include the Up-flow Anaerobic Sludge Blanket (UASB), the Expanded Granular Bed Reactor (EGSB) and currently, the Static Granular Bed Reactor (SGBR), all of which produced a high removal of organic matters known as major compounds i.e. biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), or total suspended solids (TSS) (Basitere et al., 2016, Basitere et al., 2017). These experiments were undertaken at the laboratorial scale. To upscale these reactors to industrial scale, they would need to be modelled prior to using them at a large scale in wastewater treatment plants (WWTPs). For that purpose, mathematical modelling of WWTP is deemed suitable to be capable of predicting the response of the WWTP under different operational settings. Additionally, it is an appropriate instrument for design modification, investigation, process control, and optimization of proposed WWTPs technology. Due to the ongoing increase of poultry slaughterhouse industries especially in South Africa, there is a need of WWTPs modelled and geared towards the optimization of pollutant removal especially for small scale businesses, i.e. slaughterhouses, which have challenges in meeting regulations imposed by local municipalities; in particular, wastewater discharge standards. Thus, this study focusses on the simulation of a miniaturized poultry

slaughterhouse wastewater treatment plants to predict their performance. The research aim was based on the assistance of small-scale poultry slaughterhouse industries in treating their wastewater prior to discharge into the receiving environment or into municipal sewer systems.

1.2. Research problem statement

Wastewater treatment plants (WWTPs) are combination of complex of chemical, biological and physical processes geared to lessen the challenges originating from polluted wastewater. Nowadays, legislation directives are proposing severer wastewater discharge restrictions, particularly for phosphorus and nitrogen in effluent destined for WWTP treatment (Sakar et al., 2009). Prior to the construction of any treatment plant, process simulation provides for design optimization, and modification, prior to the construction of the WWTP. For this, available simulation models such as the anaerobic digestion model No. 1 (ADM1) for mathematical modelling for anaerobic digestion processes was developed by the international water association (IWA) task group with the aim being to facilitate the development of most advanced models for full-scale industrial plants. The model facilitates operational investigation and process control evaluation, assisting in treatment technology development from research to industry, easing a mutual basis for further industrial validation studies and operation development (Henze et al., 2000). Both, the ADM1 and another model, i.e. the anaerobic sludge model (ASM1 model) have not been applied in research studies to simulate miniaturized poultry slaughterhouse wastewater (PSW) treatment plants. So, considering the prospective advantages in modelling and ongoing research of implementing wastewater treatment to increase water re-usage, the anaerobic digestion of high strength wastewater, such as PSW warranted a research study to simulate a small-scale PSW treatment plant which can be used by miniature/small scale operators to treat their poultry slaughterhouses wastewater.

1.3. Research questions

- Can Sumo be used as a simulator to model high strength wastewater such as poultry slaughterhouse wastewater treatment?
- How would the WWTP simulation produced to be beneficial to the small poultry slaughterhouse industries in South Africa?

1.4. Research aim and objectives

The general aim of this study was to simulate a small-scale wastewater treatment plant for the treatment of PSW, for the benefit of small-scale operators.

The definite objectives of this study were therefore:

- With the aid of Sumo modelling software, to design a system to treat poultry slaughterhouse wastewater at a small scale.
- To assessment the performance of the designed model especially in term of nutrients removal from the poultry slaughterhouse wastewater.

1.5. Significance of the research

Poultry slaughterhouse wastewater (PSW), is one of the most detrimental discharged pollutants in South Africa and globally, due to its characteristics. To gain a competitive advantage small-scale poultry products producer require simplified designs for their small PSW treatment plants to adequately treat the wastewater generated. Wastewater discharged by poultry slaughterhouses is characterized mainly by high biochemical oxygen demand, high suspended solids and a complex mixture of fats, proteins and solids requiring systematic treatment prior to disposal and/or reuse. This research provides a plausible alternative for meeting legislative requirements for small poultry slaughterhouse industries, as to develop unsophisticated technologies for the treatment of their wastewater at low cost and discharge it safely without penalties.

1.6. Delineation of the research

The scope of the research is solely focused on wastewater from the poultry slaughterhouse industry with a regional focus of Cape Town, South Africa. Furthermore, only Sumo will be used as a modelling software due to its low cost and a single license user fee.

CHAPTER 2
LITERATURE REVIEW

CHAPTER 2
LITERATURE REVIEW

2.1. Characteristic of poultry slaughterhouse wastewater

Poultry slaughterhouses are known to produce excessive amounts of wastewater containing high volume of biodegradable organic matter, suspended and colloidal matter such as fats, and proteins (Basitere et al., 2017). Common slaughterhouse wastewater (SWW) effluents characteristics have been described in previous research studies and are summarized in Table 2.1. Bustillo-Lecompte and Mehrvar (2015a) reported that the SWW is usually evaluated in terms of bulk parameters due to the specific amounts of pollutants loads from the animals slaughtered and processes that are used for meat processing among individual meat processing facilities. These parameters are, but not limited to the following parameters: BOD_5, COD, TDS, TSS and FOG (Barbut, 2015). The high concentration of COD indicates the presence high chemical reaction between organic substances in wastewater (Bustillo et al, 2016).

Table 2.1: Characteristic of poultry slaughterhouse wastewater (adapted from Barbut, 2005).

Parameter	Range	Mean
TOC (mg/L)	70–1200	546
BOD_5 (mg/L)	150–4635	1209
COD (mg/L)	500–15,900	4221
TN (mg/L)	50–841	427
TSS (mg/L)	270–6400	1164
pH	4.90–8.10	6.95
TP (mg/L)	25–200	50
Orto-PO_4 (mg/L)	20–100	25
Orto-P_2O_5 (mg/L)	10–80	20
K (mg/L)	0.01–100	90
Color (mg/L Pt scale)	175–400	290

The major source of contamination contained in the SWW is as result of blood, stomach and intestinal contents, including carcass debris. Moreover, SWW comprises of high levels of organics, pathogenic and non-pathogenic microorganisms, and chemical sanitizers such chlorine and ammonia products used during cleaning activities (Youn et al., 2017). It is for this reason that, SWW is regarded as detrimental to environmental health, as a result of its

composition of proteins, fats and debris from the slaughtering process; therefore, it is essential that such wastewater is treated prior to discharge into municipal sewer systems or into receiving bodies such as rivers.

2.2. Regulations governing discharge of poultry slaughterhouse wastewater in South Africa

Regulations are essential to mitigate against the environmental impact caused by mis-management or illicit discharge of PSW in municipal sewer systems. In South Africa (SA), regulation related to wastewater management practices and industrial discharge standards are respectively governed by the National Water Act (Act 36 of 1998) (NWA) and Water Services Act (Act 108 of 1997) (WSA). Some large-scale South African poultry slaughterhouses discharge their wastewater after appropriate treatment into municipal sewers. However, discharges into municipal sewers are not regulated under the NWA but are instead regulated by the WSA.

The Department of Water Affairs (South Africa) (DWASA) developed the Waste Discharge Charge System (WDCS) framework to promote water conservation and waste reduction. **It** is part of the pricing strategy for wastewater discharge and is being established under the National Water Act (Act 36 of 1998). It contains 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 (DWASA, 1996).

As a consequence of the WCDS, it is mandatory for the poultry slaughterhouses that have the permission to discharge their treated wastewater into municipal sewer systems to abide by local municipal by-laws for each municipality, as set by the Water Services Act of 1997 (Molapo, 2009). For instance, as all the poultry slaughterhouses in the Western Cape Province must comply with the City of Cape Town Wastewater (CCT) and Industrial Effluent By-law (2013), penalties and levies are administrated to the industries that fail to comply with these regulations. According to the City of Cape Town (Western Cape, South Africa), wastewater and industrial discharge by-law (2006), Schedule 1 (1) (2), discharge tariff penalty can be levied based on a formula as listed in Eq. 2.1.

$$Cost = Vw(SVC) + VieT(COD- 1000)/1500 + VieT(SF) \quad (2.1)$$

Where:

Vw = total volume (*kL*), of wastewater discharged from the premises during the period under assessment,
SVC = sewerage volumetric charge in terms of the sanitation tariff,
Vie = total volume (*kL*) of industrial effluent discharged from the premises during the period under assessment,
T = cost, as determined by the council, of treating 1kL of wastewater, and
COD = chemical oxygen demand (mg/L) of the effluent.

In cases when COD is <1000 mg/L, the COD factor falls away, with a surcharge factor being another way to ensuring compliance. A surcharge factor (SF) of the effluent can be calculated according to Eq. 2.2.

$$SF = (X - L)/L \quad (2.2)$$

Whereby:
X = concentration of one or more of the parameters listed in Schedule 2 (see Table 2.2), and
L = being the limit applicable to that particular parameter.

Table 2.2: Discharge standards of wastewater into sewer systems in Cape Town.

Parameter	**Not less than**	**Not to exceed**
Temperature at point of entry	0°C	40°C
pH Value at 25°C	5.5	12.0
COD	-	5000 mg/L
Settleable solids (60 min)	-	50 mg/L
Suspended solids	-	1000 mg/L
Total Dissolved solids at 105°C	-	4000 mg/L
Total Phosphates as P	-	25 mg/L
Total cyanides as CN	-	20 mg/L
Total sulphides as S	-	50 mg/L
Oils, greases, waxes and fat	-	400 mg/L

Basitere et al., 2016; City of Cape Town, 2016

The South African National Water Act and South African National Accreditation System (SANAS) standards (Metcalf & Eddy, 2003) are used as a threshold to monitor effluent discharged into municipal wastewater systems. This is done through the quantification of chemical parameters such as BOD_5, COD, pH, suspended solids, oxygen absorption,

nitrogen and phosphorus concentration etc. From the same by-law, i.e. in Schedule 2, the parameters as depicted in Table 2.2 (Basitere *et al*., 2016; City of Cape Town, 2016) are forbidden from being exceeded when discharging wastewater into the municipal sewer systems.

2.3. Poultry slaughterhouse wastewater treatment

Slaughterhouse wastewater is a typical organic wastewater rich of high concentrations of BOD (150–4635mg/L), COD (500- 15900mg/L) (refer to Table 2.1). For instance, Basitere et al. (2017) reported 2133–10655mg/L COD and 1100–2750mg/L BOD in raw poultry slaughterhouse wastewater from a small-scale slaughterhouse located in the Western Cape (SA). These characteristics classify slaughterhouse wastewater as being highly polluted, i.e. high strength wastewater. Therefore, slaughterhouse wastewater must be treated prior to its discharge into receiving waters to eradicate its negative effects on the receiving environment and animal health (Salminen and Rintala, 2002).

The fundamental principles of poultry slaughterhouse wastewater treatment include: preliminary treatment which entails the removal of large objects, fats and grit. In primary treatment, flocculated particles are skimmed from the surface and heavier particles are removed by quiescent settling and/or sedimentation. Subsequent to primary treatment, advanced primary treatment ensures further removal of flocs whereby flocculants such as aluminum sulfate and ferric sulfate are added to enhance sedimentation and removal of agglomerated lighter suspended solids. For example, Tari et al. (2012) used flocculating technology for the removal of Total Phosphorous (TP), TSS and COD reduction from SWW. Results which showed maximum COD, TP and TSS removal efficiencies of up to 65,34 and 98%, respectively; with residual organic matter, nitrogen and phosphorus present in the treated SWW being further removed in some downstream treatment operations.

Additional combinations of physical, chemical and biological processes can be used to include tertiary treatment systems such as membrane bioreactor technology for the removal of minute residual pollutants. It is important that the SWW go through these stages of treatment for it to meet municipal discharge standards for safe disposal even for recycling. Failing to meet such requirements, untreated SWW could have tremendous impact onto the receiving water bodies and subsequently animal health.

2.4. Environmental impact and health effects of slaughterhouse wastewater

The detrimental effect that slaughterhouse wastewater has on watercourses cannot be overemphasized. Although the environment through natural cleansing processes handles a certain amount of pollutants, as the concentration of pollutants/toxicants increases, these mechanisms come to be exhausted and inefficient.

The discharge of raw SWW causes deoxygenation of rivers leading to the contamination of surface and groundwater bodies. Ojekunle and Lateef (2017) investigated the environmental impact of slaughterhouse wastewater, on the quality of surface water and groundwater in Abeokuta (Nigeria). The results showed that the major source of surface and groundwater pollution in the study area was from a discharge of untreated wastewater from a slaughterhouse located in the vicinity of surface water bodies, resulting in grave surface and groundwater contamination. Further, Eze and Eze (2018) also reported the effect of slaughterhouse wastewater on the physicochemical and bacteriological qualities of new-artisan river in Enugu (Nigeria), revealing that the Enugu River (Nigeria) was polluted and unfit for potable water supply due to untreated slaughterhouse effluent being discharged into the river increasing bacterial growth, leading to death of aquatic life. The chemical oxygen demand detected in the samples was 3820 mg/L, in comparison to drinking water guidelines which must have a COD (max) of 100 mg/L (Edition, 2011).

Furthermore, SWW contains high levels of pathogenic and non–pathogenic microorganisms, organic matter, and surfactants used for cleaning purposes. Detergents are major components of surfactants and may go into the aquatic environment due to inadequate treatment and dumping of untreated SWW, resulting in short and long term changes in the ecosystem that can affect humans, aquatic life and riparian vegetation (Verheijen et al., 1996). Pathogens from SWW can also be transmitted to humans who are exposed to contaminated water bodies, making such wastewater unsuitable for swimming, or irrigation purposes. For instance, some studies at Bodija abattoir (Nigeria) have demonstrated that pathogenic organisms from untreated wastewater can find their way to dug-out wells used for drinking water in the vicinity of non-complaint slaughterhouses.

This shows that satisfactory treatment processes of poultry slaughterhouses wastewater must be performed prior to the discharge of the treated water into water bodies to minimize environmental pollution and to secure water bodies for use by humans (Adeyemo et al., 2002, Pina et al., 2000, Stets et al., 2014). It is for this reason that, various technologies have been evaluated for the treatment of PSW, which ultimately can culminate in the treated water being recycled to reduce water usage, particularly in the poultry industry, in order to

address operational inconveniences related to the lack of potable water (Bustillo-Lecompte et al., 2016). Of these technologies, anaerobic treatment has gained momentum due to its favorable operational outcomes such as the removal of high concentration of organic matter, high pathogen removal, low sludge production, biogas production and low energy consumption, with a low-plant footprint.

2.5. Anaerobic wastewater treatment of PSW

Over the past decades, several techniques have been developed to treat poultry slaughterhouse wastewater. These techniques utilize different physical, chemical and biological methods. The biological treatment method associated with aerobic treatment is mostly characterized by high operational costs, while a considerable fraction of the organic matter is converted to another type of waste (sludge). In contrast to aerobic treatment, anaerobic treatment is been proven to be the preferred biological treatment method that is applied in SWW treatment due to its efficiency in treating wastewater with high organic matter concentration (Cao and Mehrvar, 2011).

During anaerobic treatment, organic matter undergoes fermentation and is degraded by different bacteria into CO_2 and CH_4 in the absence of oxygen including low concentrations of ammonium-based compounds. The advantage of anaerobic systems includes low sludge production (5-20%), removal of high COD in comparison to the aerobic systems. And also, it requires less energy with a potential of nutrient and biogas recovery for plant heating requirements (Bustillo-Lecompte et al., 2014).

2.6. Stages of anaerobic digestion

In the anaerobic digestion process, microorganisms degrade organic matter in four phases – hydrolysis, acidogenesis, acetogenesis and methanogenesis. Each stage is dominated by specific bacterial population. The digestion is incomplete unless the organic matter has undergone the four phases.

In the hydrolysis phase, through catalytic reactions, complex organic matter is broken-down by enzymes into monomers such as sugars, amino or fatty acids. According to Al-Ghouti et al. (2003), this phase is relatively slow, mainly due to cellulolytic constituents in the wastewater which are generally not treated anaerobically. During acidogenesis, microorganisms convert the monomers into simple organic compounds through fermentation

with the product that originates from this phase being short-chain acids, ketones and alcohols.

Subsequent to the acidogenesis phase, is the acetogenesis phase, whereby, bacteria convert acids and alcohols into acetate, hydrogen and CO_2. The products produced at this stage are dependent on the type of bacteria including environmental conditions, such as pH and temperature (Ostrem, 2004). The conversion of organic material into organic acids leads to a drop of pH (4.5 to 5.5), which benefits the acidogenic and acetogenic bacteria that prefer a slightly acidic environment.

During the last stage, known as methanogenesis or methane fermentation, the production of CH_4 and CO_2 (biogas) is carried-out under strict anaerobic condition by the methanogenic bacteria from intermediate by products. Methanogenesis is critical stage, in the entire anaerobic digestion process, because it is the slowest biochemical reaction of the process (Muha, 2013).

Below are the typical reactions during anaerobic digestion:

Hydrolysis

$$C_6H_{10}O_4 + 2H_2O \rightarrow C_6H_{12}O_6 + H_2 \quad (2.3)$$

Acidogenesis

$$C_6H_{12}O_6 \rightarrow 2CH_3CH_2OH + 2CO_2 \quad (2.4)$$

Acetogenesis

$$CH_3CH_2COO^- + 3H_2O \rightarrow CH_3COO^- + H^+ + HCO_3^- + 3H_2 \quad (2.5)$$

Methanogenesis

$$CH_3COOH \rightarrow CH_4 + CO_2 \quad (2.6)$$

2.7. Assessment of technologies performed in the treatment of poultry slaughterhouse wastewater (PSW)

The typical technologies for PSW anaerobic treatment include, anaerobic treatment using Aerobic Moving Bed Biofilm Reactor (MBBR), Aerobic Reactors (AR), Up-Flow Anaerobic Sludge Blanket (UASB), Anaerobic Sequencing Batch Reactor (SBR) and Expanded Granular Sludge Reactor (EGSB). Njoya (2018) stated that “these bioreactors are all systems with dispersed bacterial growth, i.e. they rely significantly on the ability of the biomass to form flocs and settle”. Their design, functionality and efficiency of all these bioreactors are discussed in the subsequent subsections.

2.7.1. Up flow anaerobic sludge blanket (UASB) technology

The UASB technology was newly introduced by Lettinga and his co-workers in the late 1970's and firstly applied by the Dutch sugar industry. Initially, the UASB reactor was designed to treat industrial wastewater but the scope of its application was later expanded to incorporate treatment of sewage wastewater. At present, the reactor is extensively used to treat several types of wastewater, thus forming part of high rate anaerobic technology bioreactors.

The UASB scheme basically comprises of an influent tank, cylindrical or rectangle column, gas/liquid/solid (GLS) separator, effluent outlet, gas outlet and a gas collection system. The schematic diagram of a UASB reactor is shown in Figure 2.1. A major advantage of the technology is its cost effectiveness when compared to an anaerobic filter. Though the technology requires less investment, it has a long start-up period. Furthermore, its workability relies on sufficient amount of granular seed sludge for a rapid start-up (Rajeshwari et al., 2000).

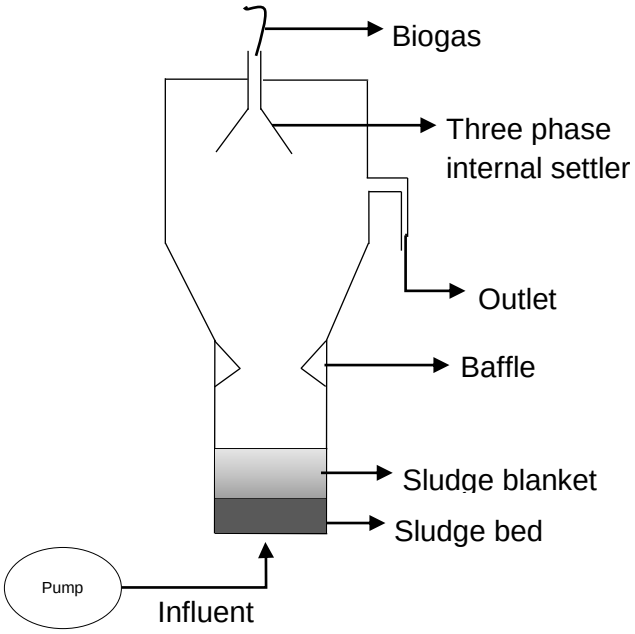

Figure 2.1: Up flow anaerobic sludge blanket (adapted from Schmidt et al.,1996).

As shown in Figure 2.1 the sludge is at the bottom of the bioreactor. Once the reactor is seeded with anaerobic sludge, the wastewater is made to flow in the upward motion through the sludge blanket. The granules would consist of small bacterial aggregates. The occurrence of this phenomenon is highly dependent on the appropriate conditions of the organic matter in the wastewater and the availability of the nutrients, COD, pH, alkalinity,

and up-flow velocity including temperature. The size of the granules can range from 0.1 to 5mm, with higher up-flow velocity providing higher shearing forces resulting in highly compact granules (Figure 2.2).

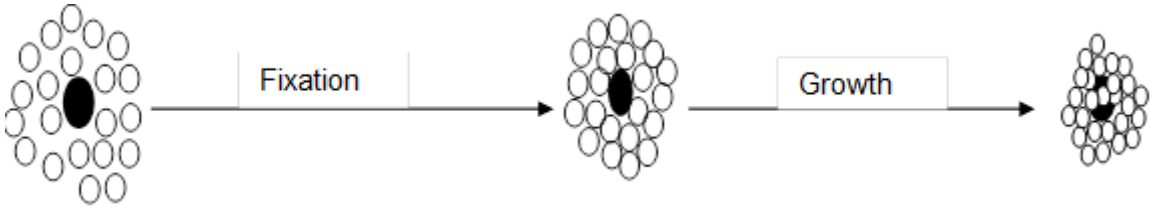

Figure 2.2: Granule formation from Sivagurunathan et al. (2006)

According to Sivagurunathan et al. (2006), the top layer of the dense sludge-bed consists of a sludge blanket zone with a much-diversified growth and lower particle settling velocities. Sivagurunathan et al. (2006) also highlighted that in the UASB, the biological reaction occurs between the highly activated sludge and blanket zone. As the wastewater moves upwards, anaerobic bacteria convert organic material into biogas consisting mainly of CH_4 and CO_2 including a minute quantity of biomass whilst purifying the wastewater (Del Nery et al., 2001). The Gas Liquid Solid (GLS) separators' primary function is to separate solids particles from the sludge/solids including biogas, while the baffles hold the viable bacterial matter in place by sliding the settled solids back to the reaction zone increasing the sustainability of the bioreactor over longer operational periods.

2.7.2. Static Granular Bed Reactor (SGBR)

The Static Granular Bed Reactor is a novel down-flow high rate anaerobic bioreactor introduced for the first time by Ellis (2000) at the IOWA University for treatment of medium to low strength wastewater. Treatment similar to the UASB, the SGBR is operated at a low cost. There is minimal mechanical mixing nor a solids/liquid separator or other mechanical device required in the SGBR system (Mach and Ellis, 2000).

In addition, the SGBR make use of a bed of active anaerobic granules for treatment of wastewater with relatively small reactor volume sizes. Thus, offering significant energy savings. The system comprises of an inlet flow distribution system and the produced biogas is separated from the granules and wastewater effluent (Mach and Ellis, 2000). The biogas can be collected at the upper end of the reactor as shown in Figure 2.3.

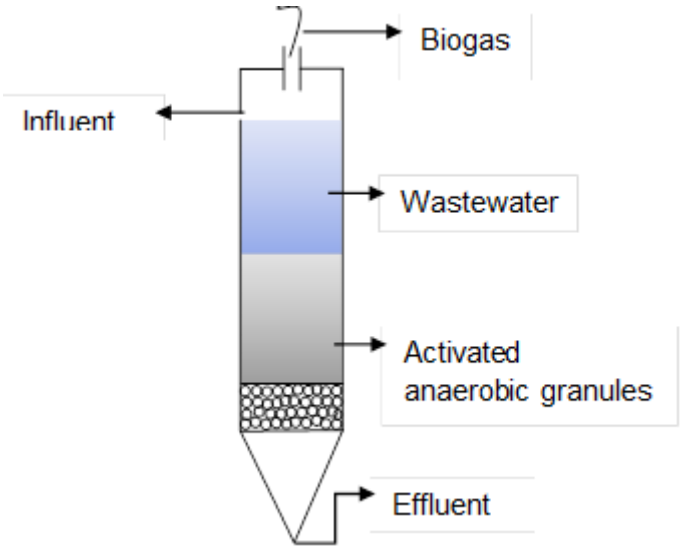

Figure 2.3: Static Granular Bed Reactor (adapted from Debik and Coskun, 2009).

As the influent wastewater enters the SGBR reactor, it pneumatically mixes with the bulk liquid via an opposite direction movement of biogas and the liquid being treated such that, a high concentration of organic matter in the influent is evenly dispersed within the sludge. SGBR also works like an anaerobic bio-filter since it involves no mixing systems and has stable granules which entraps solids incoming in the bioreactor (Del Nery et al., 2001). Because the whole bed is active during influent treatment, this reactor configuration allows simple operational procedures, smaller volume requirements and subsequently for good effluent quality.

The effluent produced as a result of that, has low residual concentration of COD, TSS, and volatile acids (VAs) which may allow it to be discharged to surface water with no additional treatment in some instances; in other words, the effluent emitted from the system routinely meets a 30 mg/L BOD_5 and 30 mg/L TSS effluent standard limit (Evans, 2004).

2.7.3. Expanded granular sludge bed (EGSB)

Similar to the UASB reactor, the EGSB relies on the self-immobilization properties of anaerobic bacteria and the development of granular biomass with good settling properties. The contact between sludge and wastewater in the EGSB is quite significant compared to the UASB. In this system, effluent recirculation is used to enhance the substrate-biofilm contact area. It is for this reason that various experts from different countries classified this system as a high-rate anaerobic reactor (Kato et al., 1994). The design of the EGSB is illustrated in Figure 2.4.

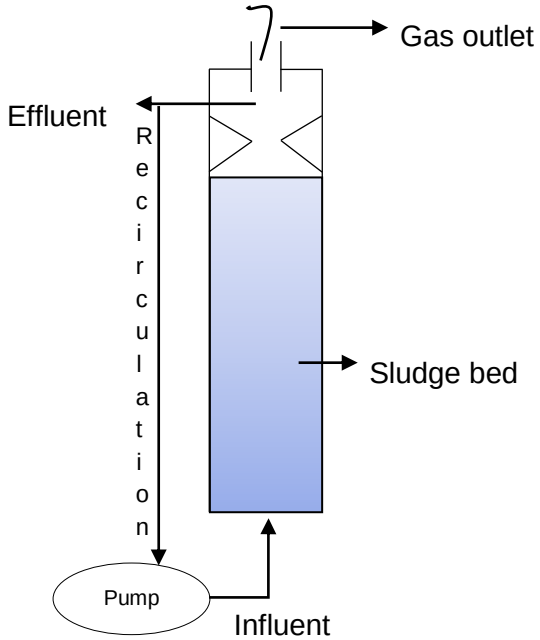

Figure 2.4: Expanded granular sludge bed (adapted from Song, 2018)

The reactor is in fact a vertically stretched version of the UASB reactor with a height of 12-16m with a loading capacity rate of 15-25 kg COD/m^3.day, resulting in an even more reduced plant foot print (Del Nery et al, 2001). The EGSB like the UASB reactor separates the biomass, biogas and wastewater in a single-step using three phase separators at the top of the reactor. Nevertheless, Basitere et al. (2016) after using the EGSB to treat poultry wastewater, reported periodic sludge wash-out from the system.

CHAPTER 3

MATHEMATICAL MODELLING AND WWTP SIMIULATION

CHAPTER 3
MATHEMATICAL MODELLING AND WWTP SIMULATION

3.1 Introduction

Worldwide, mathematical modelling of wastewater treatment seems to be an answer to the question as to how WWTP will react under various operating conditions. It has become a widely accepted tool for the design, analysis, control, forecasting and optimization of WWTPs, thus helping to assure high effluent quality. In an effort to meet the strict effluent limits or standards new models and model's extensions are being developed constantly.

One of the millstones in dynamic modelling of WWTPs was the research conducted by the University of Cape Town (Ekama and Marais, 1977). This dynamic model originated from the steady state model of Marais and Ekama. (1976). Then, in 1987 a task group led by Prof. Henze introduced the first Activated Sludge Model for biological carbon and nitrogen removal known as ASM1. The so called "state of the art models" were developed based on the University of Cape Town (UCT) model, albeit presented in a new format and with a new and standardized notation. The ASM1 model was not designed to perform excess biological phosphorus removal (EBPR). Thus, the task group extended ASM1 to include EBPR ASM2 and ASM2d (Henze et al., 1999). In parallel work, the task group developed ASM3 which simulates carbonaceous energy removal, including nitrification and denitrification (Koch et al., 1999).

The need to widen the model boundaries and to include other process units led to the development of the Anaerobic Digestion Model No. 1 (ADM1) proposed in 2002 as a common platform for designing, developing, and validating models of anaerobic digestion processes (Batstone et al., 2002). Over the years, ADM1 model has become one of the practical dynamic tools for modelling anaerobic digestion.

3.2. Model description

The AMD1 model was developed by the international water association (IWA) for mathematical modelling of anaerobic digestion processes as extensively discussed in the paper published by an IWA Task group (Batstone et al., 2002). The following is rather a brief summary of the model for discussion purposes.

ADM1 is an organized generic model that portrays the major process describing biochemical and physicochemical processes involved in the breaking down of complex organic matter into biogas and inert by-products (Batstone et al., 2012). ADM1 is a mathematical model grounded on COD as a common unit used in wastewater characterization representing the performance of the organic substrates removal (Boubaker and Ridha, 2008).

The organic components considered by the model are the following: complex particulates, proteins, carbohydrates, sugars, lipids, amino acids (AA), long chain fatty acids (LCFA), volatile fatty acids and particulate and soluble inert substrates (Karakashev et al., 2006). Figure 3.1 illustrates the substrate and conversion processes pertaining to the presented model.

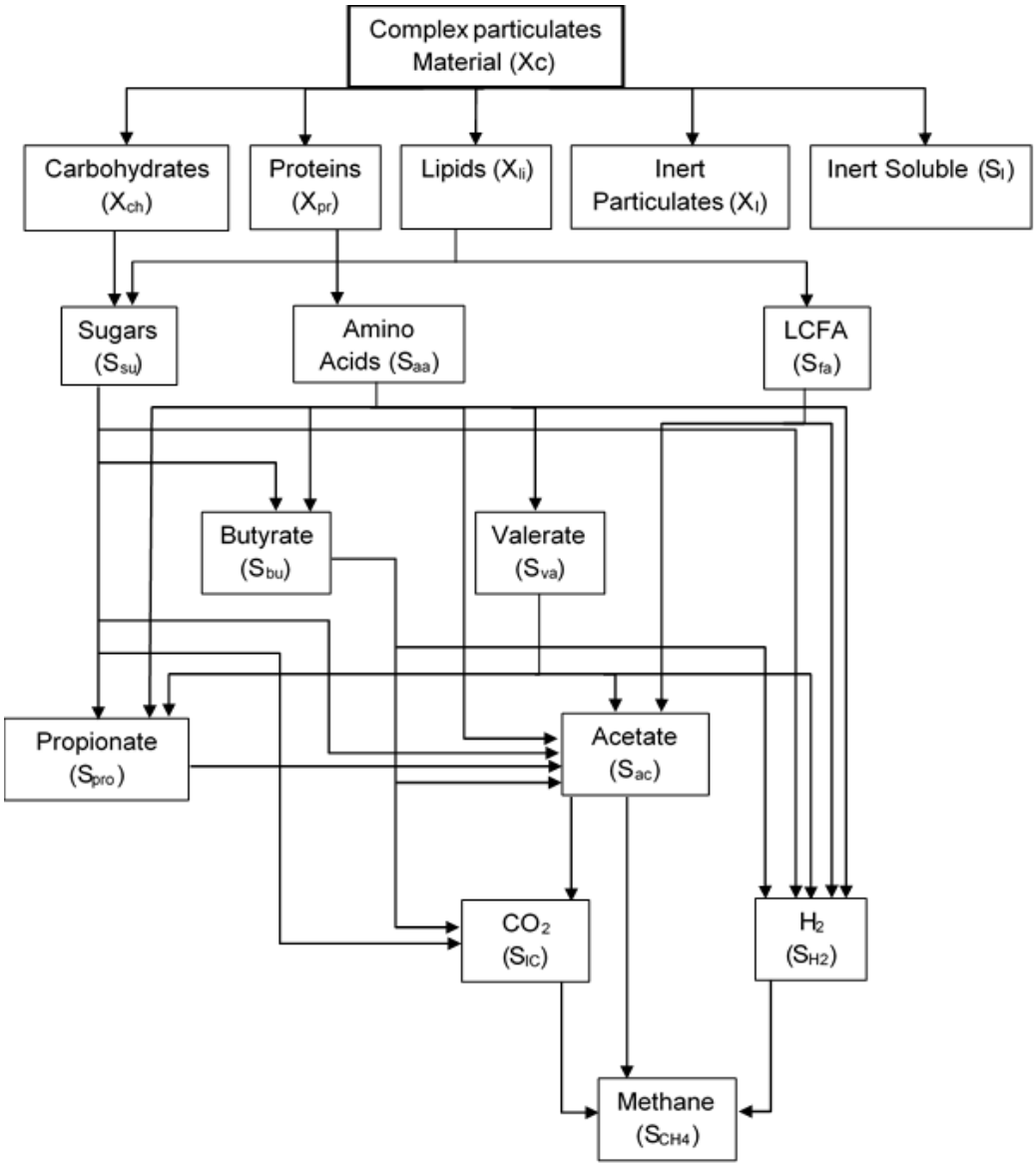

Figure 3.1: Biochemical conversion processes according to ADM 1 model (adapted from Boubaker and Ridha, 2008)

The first biochemical conversion in digesters involves the breakdown of complex particulate matters to monomer constituents of proteins, carbohydrates, lipids, particulate and some soluble inert substrates. Hydrolysis of particulate monomers is the next conversion step with carbohydrates, proteins and lipids are converted into sugars, Amino Acids (AA) and Long Chain Fatty Acids (LCFA) by hydrolytic bacterial species. Once particulate monomers are hydrolysed, then the fermentation of AA ensues to produce CO_2, hydrogen and AA (acidogenesis) (Derbal et al., 2009). Subsequently anaerobic oxidation of propionic acid, valeric acid, butyric acid into CO_2 and hydrogen gas including acetate (acetogenesis) ensues. The last step involves the production of biogas, which takes place in two ways; either based on the acetate or through the reduction of CO_2 by molecular hydrogen (Boubaker and Ridha, 2008).

3.3. Model equations

The ADM1 model is an organized mathematical model comprising of 32 dynamic state variables to model change of different species for both in-/soluble and particulate components contained in the gaseous and liquid phases. Table 3.1 depicts the dynamic state variables contained in AMD1 model (Copp et al., 2003).

In the ADM1 model, the total COD is a composite variable calculated through the addition of the organic state variables. Equations 3.1, 3.2, 3.3 shows how total COD is estimated for the ADM1 model.

$$COD_{soluble} = S_i + S_{su} + S_{aa} + S_{fa} + S_{va} + S_{bu} + S_{pro} + S_{ac} + S_{h2} + S_{ch4} \quad (3.1)$$

$$COD_{particulate} = X_i + X_{su} + X_{aa} + X_{fa} + X_{c4} + X_{pro} + X_{ac} + X_{h2} + X_c + X_{ch} + X_{pr} + X_{li} \quad (3.2)$$

$$COD_{total} = COD_{soluble} + COD_{particulate} \quad (3.3)$$

Table 3.1: List of the dynamic state variables in ADM1 model.

	Variables	Symbol	Units
Particulate	Composites	X_c	Kg COD m^{-3}
	Carbohydrates	X_{ch}	Kg COD m^{-3}
	Proteins	X_{pr}	Kg COD m^{-3}
	Lipids	X_{li}	Kg COD m^{-3}
	Particulate inerts	X_I	Kg COD m^{-3}
Soluble	Monosaccharides	S_{su}	Kg COD m^{-3}
	Amino acids	S_{aa}	Kg COD m^{-3}
	Long chain fatty acids	S_{fa}	Kg COD m^{-3}
	Valerate	S_{va}	Kg COD m^{-3}
	Propionate	S_{pro}	Kg COD m^{-3}
	Butyrate	S_{bu}	Kg COD m^{-3}
	Acetate	S_{ac}	Kg COD m^{-3}
	Soluble inerts	S_i	Kg COD m^{-3}
	Hydrogen gas	S_{h2}	Kg COD m^{-3}
	Methane gas	S_{ch4}	Kg COD m^{-3}
	Sugar degraders	X_{su}	Kg COD m^{-3}
	Amino acid degrader	X_{aa}	Kg COD m^{-3}
	LCFA degrader	X_{fa}	Kg COD m^{-3}
	Valerate and butyrate degraders	X_{c4}	Kg COD m^{-3}
	Propionate degraders	X_{pro}	Kg COD m^{-3}
	Acetate degraders	X_{ac}	Kg COD m^{-3}
	Hydrogen degraders	X_{h2}	Kg COD m^{-3}
	Inorganic nitrogen	S_{in}	Kmole N m^{-3}
	Inorganic carbon	S_{ic}	Kmole C m^{-3}
	Anions	S_{an}	Kmole m^{-3}
	Cations	S_{cat}	Kmole m^{-3}

3.3.1. Liquid phase equations

The mass balance equations utilized by the ADM1 model to describe the dynamic behaviour of soluble and particulate substrates in the liquid phase are shown in Eq. 3.4 and 3.5 Fedorovich et al. (2003).

$$\frac{dS_{liq,i}}{dt} = \frac{Q}{V_{liq}}.(S_{in,i} - S_{liq,i}) + \sum_{j=1-19} \rho_j v_{i,j} \qquad \text{i=1…12; i=25-26} \qquad (3.4)$$

$$\frac{dX_{liq,i}}{dt} = \frac{Q}{Vliq}.(X_{in,i} - X_{liq,i}) + \sum_{j=1-19} \rho_j v_{i,j} \qquad \text{i=13,…,24} \qquad (3.5)$$

Where:

$S_{liq,i}$: concentration of each soluble state variable,

$X_{liq,i}$: concentration of each particulate and biomass state variable,

V_{liq}: liquid reactor volume,

Q: flow in and out of the reactor,

$S_{in,i}$: input concentration of soluble components,

$X_{in,i}$:concentration of particulate and biomass components,

$\sum_{j=1-19} \rho_j \nu_{i,j}$: is the sum of the specific kinetic rates ρ_j for process j multiplied by the stoichiometric coefficients $V_{i,j}$.

3.3.2. Gas phase equations

Three main gaseous components modelled by the ADM1 model in the gas phase are biogas constituents. The rate transfer of these gas can be attained by applying the theory of two-film developed by Whitman (Whitman, 1923). Eq. 3.6 is an expression of the general dynamic gas concentration of each gas component "*i*".

$$\frac{dS_{gas,i}}{dt} = \frac{q_{gas}}{V_{gas}} S_{gas} + \frac{V_{liq}}{V_{gas}} \rho_{T,i} \qquad (3.6)$$

Where:

q_{gas}: gas flow,

V_{liq}: liquid reactor volume (l),

V_{gas}: gas volume (l);

S_{gas}: gas phase concentration of gas component "i",

$\rho_{T,i;}$ specific mass transfer rate of gas "i" expressed as in Eq. (3.7):

$$\rho_{T,i} = K_{La}.(K_H.P_{gas,i} - S_{liq,i}) \text{ i=Ch}_4, \text{ CO}_2 \text{ and H}_2 \qquad (3.7)$$

Where:

K_{La}: volumetric gas liquid mass transfer coefficient,

K_H (*M bar-1*): henry's law coefficient,

S_{liq} (*M*): liquid phase concentration of gas component "i",

P_{gas}: gas phase pressure of each gas component "i" calculated from the ideal gas law as follows Eq. (3.8):

$$p_{gas,H_2} = S_{gas,H_2}.\frac{R.T_{op}}{16} \quad (3.8)$$

$$p_{gas,CH_4} = S_{gas,CH_4}.\frac{R.T_{op}}{64} \quad (3.9)$$

$$p_{gas,CO_2} = S_{gas,CO_2}.R.T_{op} \quad (3.10)$$

When assessing the dynamic gas phase concentration of all gas components, assuming that the total pressure of the gas phase is above that of the liquid, is under specified reactor temperature. The rate at which the gas is produced can be estimated as in Eq. 3.11:

$$q_{gas} = \frac{RT_{op}}{p_{atm}-p_{gas,H_2O}} V_{lip}(\frac{P_{T,H_2}}{16} + \frac{P_{T,CH_4}}{64} + P_{T,CO_2}) \quad (3.11)$$

3.4. Simulator versus biological model

A simulator and the biological model are two different artefacts. The computer program that enable the user to configure (in this context a WWTP) by tying-up various unit processes (reactor, clarifier etc.) together according to the flow scheme of a particular treatment plant, and then simulate the performance of the plant for specified operational and influent loading conditions. Whereas, the model to be used is actually the set or sets of equations that are solved within the simulator (Melcer, 2004). Table 3.2 summaries information on some of the most popular simulators which are capable to accomplish the research task for this study.

Table 3.2: Popular wastewater simulator (adapted from Melcer, 2004)

Simulator	Vendor	Location
ASIM	EAWAG (Swiss Federal institute for Environmental Science & Technology)	Switzerland
BioWin	EnviroSim Associates Limited	Canada
WEST	Hemmis N.V.	Belgium
GPS-X	Hydromantic, Inc.	Canada
SUMO	Dynamita SARL	France
STOAT	WRe Group	United Kingdom

3.5. SUMO simulator

Sumo (Dynamita, France) is an innovative, open software wastewater process modelling software, having a multipurpose simulation platform developed for numerous environmental models, particularly for municipal and industrial wastewater treatment. A variety of plant designs can be simulated in Sumo. The models in the simulator are written in MS Excel based on open source code language called SumoSlang (Sumo Simulation Language, copyright Dynamita), thus imparting simulation ease in which both, steady-state and dynamic simulations can be performed.

Sumo can simulate in steady-state, traditional bio-kinetic, mixed equilibrium-kinetic and direct algebraic models, depending on the outcomes of the process being designed. The simulator comes with internally researched and developed wholes models including ASM models (AM1, ASM2D, ASM2D_TUD, ASM3_BioP, ASM3), Barker_Dold, BUCTPHO plus. A variety of model options can be selected:

- the calculation of the gas phase concentrations,
- the integration of the pH, and
- the chemical precipitation of some components.

Amongst all the simulators presented in Table 3.2, Sumo was selection because there is no need to create copies of the same configuration containing different sets of parameters, therefore updating the plant model becomes centralized and much easier to manage. The limitation of the software is in its instability of the hardware, especially when inputting complex process designs into the software.

CHAPTER 4

MATERIALS AND METHODS

CHAPTER 4
MATERIALS AND METHODS

4.1. Introduction

All the parameters used in the model were from previous similar studies (Njoya, 2017, Basitere et al, 2017, Rinquest, 2017) except for COD which was measured using the method as described in Mamais et al. (1993). The sample used to perform this experiment came from the PSW sourced from a poultry slaughterhouse located in the Western Cape Province (South Africa).

4.2. Fractionation of COD

The COD parameter encapsulates several forms of organic carbon that require further differentiation in relation to their biodegradation characteristics. In this context, the total influent COD in wastewater can be divided into two distinct components: the total non-biodegradable or inert COD and the total biodegradable COD. Each of these is further subdivided into other components (Orhon and Çokgör, 1997).

The non-biodegradable COD consists of two fractions: the soluble inert COD portion (S_I) and particulate inert COD portion (X_I) (Figure 4.1). Hypothetically both components are unaffected by biochemical reactions in the anaerobic reactor whereas, the particulate inert COD is subjected to entrapment and accumulation in the activated sludge and it exits the system through the sludge wastage stream (washout).

The biodegradable COD portion which originally relates to the bi-substrate model of Dold and Marais (1986), is sub-divided into two major fractions: readily biodegradable (S_s) and slowly biodegradable (X_s) COD.

The readily biodegradable portion is composed of material in a form of short chain volatile fatty acids (S_A) that can be easily absorbed by the organisms in the sludge and is metabolised for energy (Melcer, 2004). A further fractionation of readily biodegradable COD is required for modelling of excess biological phosphorus.

The slowly biodegradable fraction encompasses a wide range of particle size distribution from soluble to colloidal and larger organic particles of complex compounds. This COD fraction, was originally defined as “particulate organics” in the model developed by Dold and Marais (1986). The common feature of the particulate organics is that they require

extracellular enzymatic breakdown prior to absorption and utilization. The characterisation of this fraction by a single value for the hydrolysis rate could be a strenuous exercise, because a significant variation for various compounds in wastewaters can be prevalent. It is based on this argument that recently the slowly biodegradable COD was further subdivided into: rapidly hydrolysable COD (S_{H1}), and slowly hydrolysable COD (X_{S1}) (Wentzel, 1995).

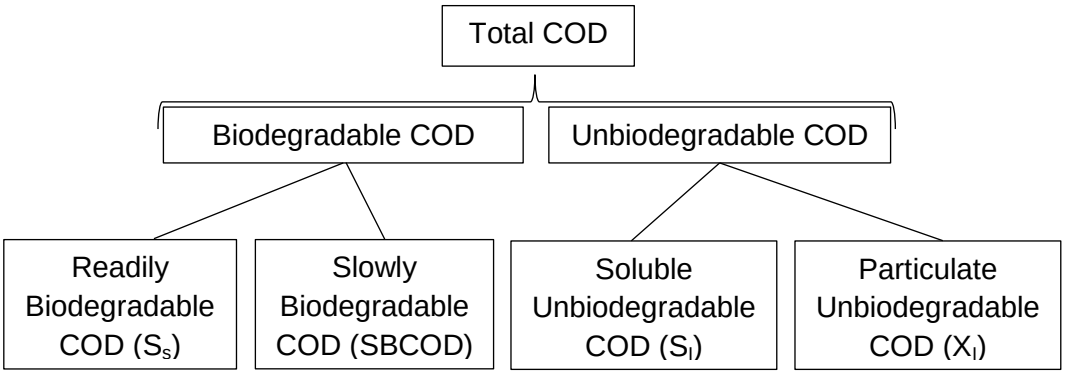

Figure 4.1: Division of the influent COD into components.

4.3. Quantification of COD

Differentiation of COD fractions can be based on its biodegradability, including filtration and flocculation see (Figure 4.2).

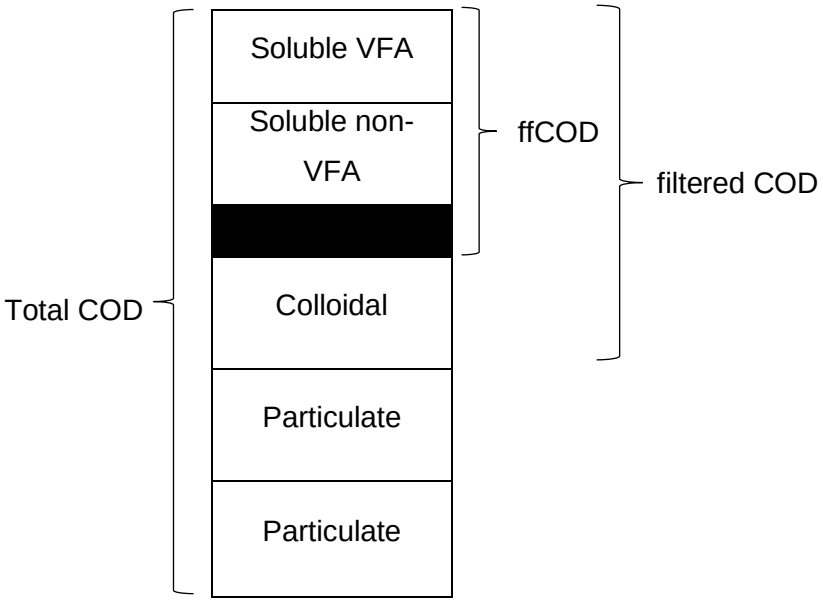

Figure 4.2: Schematic representation of COD Fractions

The total COD encompasses filtered COD and filtered flocculated COD (ffCOD) which were analysed using Merck solutions: A (1.14679.0495) and B (1.14680.0495) for high range and A (1.14538.0065) and B (1.14681.0495) for low range, with readings being recorded on a Merck Spectroquant® UV/VIS Spectrophotometer Pharo 300. This measurement includes all COD fractions measurements shown in Equation 4.1 (Figure 4.3).

$$Total\ COD = S_s + S_{col} + X_s + S_I + X_I \quad (4.3)$$

Filtered COD was determined by passing the PWS sample through a 1.0 µm glass fibre filter (Figure 4.3) and measuring the COD of the filtrate, using COD Merck test kit including methods as instructed in the manufactured manual.

Figure 4.4: Image showing the residue of PWS on the 1.0 µm glass fibre filter after filtration.

Filtered flocculated COD (ffCOD) was determined by the flocculation of the PSW followed by a filtration process as suggested by Mamais et al. (1993) with minor modifications. Figure 4.5 illustrates the flocculation filtration method. The flocculation step includes adding 1mL of zinc sulphate ($ZnSO_4$) to 100 mL of the PSW subsequent to stirring vigorously for one-minute. A 6M of sodium hydroxide was added to the solution to adjust the pH to 10.5 and allowed the wastewater to settle for a few minutes. The filtration step includes filtering the supernatant of the flocculated samples with 0.22 µm membrane filter instead of 0.45 µm filters. The use of the chemical flocculant with filtration is intended to remove colloidal COD (S_{col}) (Mamais et al., 1993). Figure 4.1 represent a depiction of test kits tubes used to measure the COD fractions.

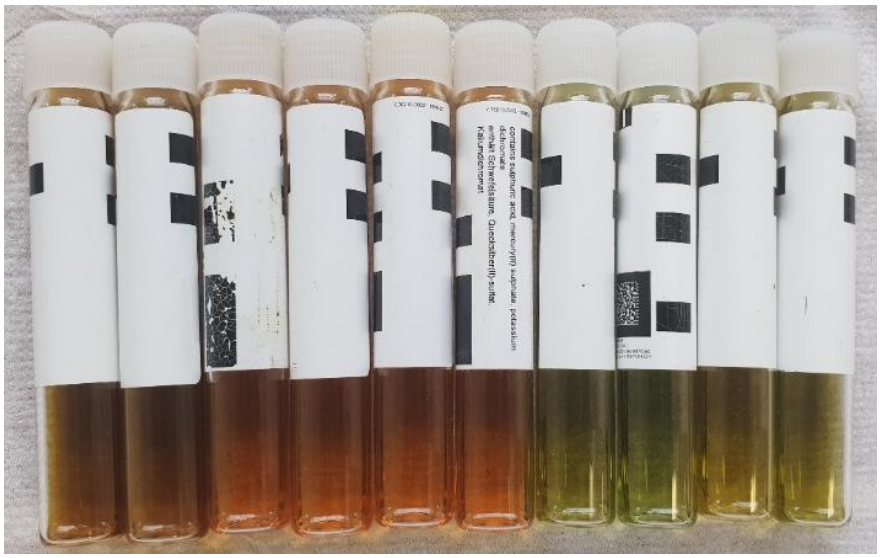

Figure 4.5: COD fractions (Total, filtered and flocculated filtered COD) in analysis test tubes

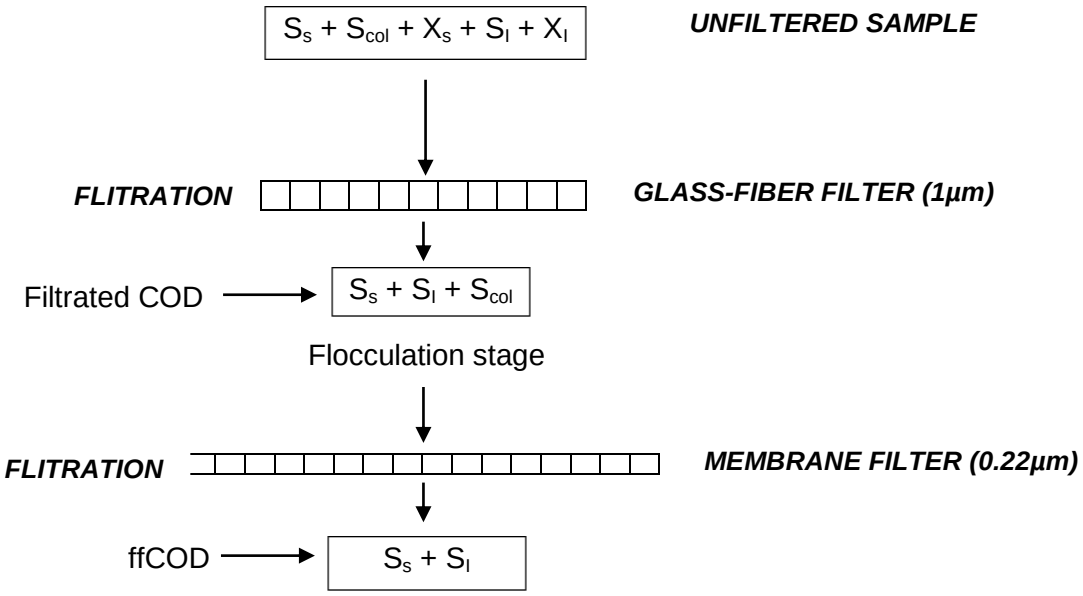

Figure 4.6: Diagram depicting the passage of PWS influent wastewater into different COD components through a 1 µm Glass-Fiber filter, Flocculation and 0.22 µm Membrane Filter

CHAPTER 5

RESULTS AND DISCUSSION

CHAPTER 5
RESULTS AND DISCUSSION

5.1. Introduction

Biological treatment processes offer undisputable economic advantages, both in terms of capital investment and operating costs over other treatment processes such as chemical oxidation and thermal oxidation (Eze and Eze, 2018). Reportedly, one of the most beneficial and advantages biological process in PSW treatment is anaerobic digestion. Anaerobic bacteria degrade organic matter inherent in PSW (Salminen and Rintala, 2002, Basitere et al., 2016, Basitere et al., 2017).

The aim of this part of the study was to simulate a small-scale wastewater treatment for the treatment of poultry slaughterhouse wastewater (PSW) for the benefit of small-scale poultry slaughterhouse in Cape Town Western Cape South Africa.

This chapter is divided into Two phases:

- **Phase 1 (Aim 1):** With the aid of Sumo, design a model for treating poultry slaughterhouse wastewater, with known PSW quality characteristics.
- **Phase 2 (Aim 2):** Assess the overall performance of the designed model especially in term of nutrients removal from the poultry slaughterhouse wastewater; being treated.

5.2. Phase 1: Poultry wastewater treatment digester configuration

5.2.1. Single stage digestion

A single-stage with completely mixed mesophilic anaerobic digestion biomass has been extensively used over the past decade in treating slaughterhouse wastewater. A single stage digester is one which all the biological processes occur in one tank (digester). The anaerobic digestion process namely hydrolysis, acidogenesis, acetogenesis and methanogenesis all take place in a single digester. In a single stage system, and for a high rate digestion process, the contents of the digester must be completely mixed while a constant temperature is maintained, to sustain a favourable environment for the mixed bacterial culture of microorganisms (mesophilic range) to effectively perform the primary function of COD reduction (Cheremisinoff, 1997).

Although the single stage system design is simpler and has a low capital costs, the process produces less biogas and the feedstock takes longer to digest resulting in high hydraulic retention time and thus low throughput rates for treating the PSW. And also, in the single

stage digester, overloading and inhibitors can lead to the accumulation of volatile organic acids which negatively impacts on biogas generation and COD removal. The inhibiting factors include insufficient trace elements and excessive macro nutrients which can lead to digester failure due to souring (Mao et al., 2015).

The digester in the single stage anaerobic digestion system designed was set to operate at steady state for 150 days under mesophilic temperature (35 ˚C) with a solid retention time (SRT) of 25 days (Figure 5.1).

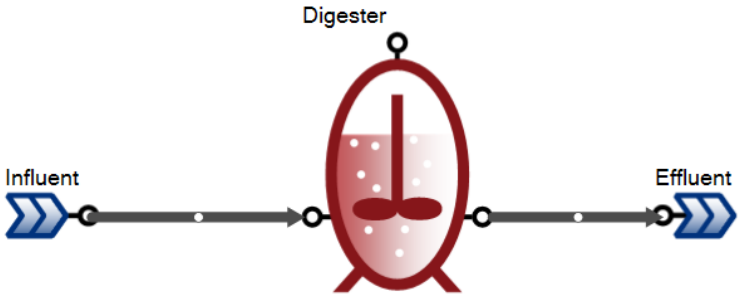

Figure 5.1: Single-stage anaerobic digestion

5.2.2. Two stage digestion

The concept of splitting the anaerobic digester into different operational stages is termed two-stage or two-phase anaerobic digestion (Blumensaat and Keller, 2005). The original idea came from Pohland and Ghosh (1971) who proposed the separation of acid-forming bacteria and methanogenic archaea into two different digesters. The intention was to favour the growth of acid-forming bacteria in the first-stage, producing volatile fatty acid (VFA) which was to be used by the methanogenic archaea in the second stage process. However, when the VFA production rate, as a result of solids hydrolysis and metabolism by the acidogenic community, surpasses the VFA assimilation capacity of the methanogenic population in the second stage, the VFA concentration is susceptible to rise to levels that could be inhibitory to the methanogenic bacteria, thus leading to an unstable operation and ultimately secondary digester failure (Schober et al., 1999).

Although several studies, i.e. Cohen et al. (1979), Siegrist et al. (1993), Anderson et al. (1994), Mao et al. (2015) have demonstrated the advantages of two-stage anaerobic digestion compared to the conventional single stage anaerobic digestion system, few disadvantages such as high capital costs and operational instability under certain environmental conditions are known as drawbacks of the two stage system configuration. However, the advantages, underline the worthiness of this innovative digestion process, thus

justifies its application and the development of a process model in which a series of digesters are used.

When it comes to a two-stage anaerobic digestion and/or multistage anaerobic digestion processes, terms such as "*series mesophilic digestion*, *acid-phase digestion* and *temperature-phased anaerobic digestion* (TPAD)" are normally used to describe such processes. In series mesophilic digestion, two or more mesophilic digesters operate in series at a sufficient SRT in the first stage to provide suitable methanogenesis conditions in the second or tertiary stages. In a TPAD process, the production of biosolids by operating the first-stage thermophilically (50 to 60°C) followed by a mesophilic digester can result in higher biogas production and digester performance. This anaerobic digestion system has also been suggested as a means to improve digester capacity through high rate thermophilic kinetics. As for acid-phase digestion, a short SRT first stage with low pH (5.5 to 6.5) is required to favour principally solids hydrolysis and fermentation to occur. This is followed by a longer SRT in the second stage at a higher pH (7 to 8) for further hydrolysis and fermentation, i.e. VFA consumption, and methanogenesis (Zahler, 2007).

The two-stage digestion system designed for poultry slaughterhouse wastewater in this study was of acid-phase digestion type. Both digesters were set to perform at mesophilic temperature (35 ˚C) at SRT of 13 days in the first digester and 25 days in the second digester. The two-stage anaerobic digestion showed better performance compared to the single-stage anaerobic digestion. A schematic diagram of the proposed design is given in Figure 5.2.

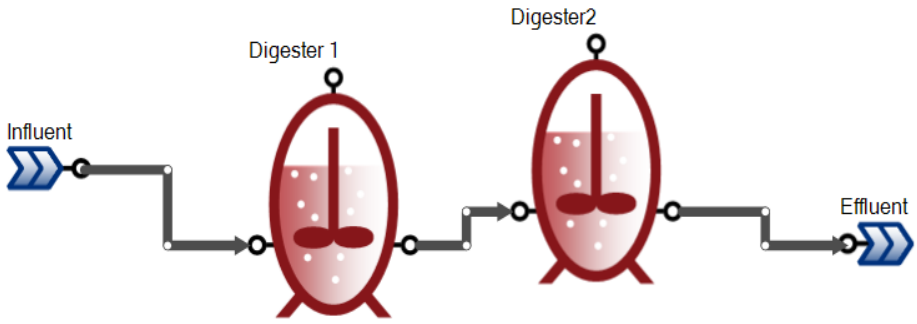

Figure 5.2: Two stage anaerobic digestion

5.3. Phase 2: Assessment the performance of the designed model in treating poultry slaughterhouse wastewater

5.3.1. PSW characterization

All the parameters used in the model were obtained from previous similar studies (Njoya, 2017, Basitere et al, 2017, Rinquest, 2017) with the exception of the COD which was measured using the method as described in Mamais et al. (1993). The PSW used was sourced from a poultry slaughterhouse located in the Western Cape Province (South Africa). The raw (untreated) PSW samples were collected in 25 L and 5 L polypropylene containers from the sump of the existing wastewater disposal facility of the poultry slaughterhouse, during slaughtering and cleaning operations. The PSW characteristic used in this study are highlighted in Table 5.1.

Table 5.1: Poultry wastewater characterisation wastewater from selected meat processing plants in the Western Cape.

Parameters	Unit	Min	Max	Average
pH	-	6.5	8	10,5
Conductivity	µS/cm	899	2450	2124
Salinity	ppm	529	1413	1235,5
Turbidity	NTU	237	997	735,5
TSS	mg/L	313	8200	4413
TDS	ppm	372	1740	1242
VSS	mg/L	232	8900	4682
NH^{+}_{4} -N	mg/L	135	447	358,5
NO_3^{+} -N	mg/L	30	235	147,5
PO_4^{3-}-P	mg/L	29	54	56
VFA	mg/L	96	898	545
Alkalinity	mg/L	360	926	823
BOD_5	mg/L	1100	5000	3600
tCOD	mg/L	2517	12490	8762
FOG	mg/L	156	1710	1011
Volatile fatty acids	mg/L	96	235	213,5

The model used requires influent wastewater characterization parameters such as TSS, VSS, TKN, TP, Alkalinity, pH, BOD_5, total COD and fractions of the COD. And also, other parameters such as VFA, ammonia, phosphate, nitrite/nitrate are needed for the model and for simulation. The other parameters used in the model are listed in Appendices A.

The ratio of COD/BOD was also calculated to evaluate the potential biodegradability of the organic contents in PSW. The ratio COD/BOD was estimated at 2.15. According to Bustillo-Lecompte and Mehrvar (2015b) wastewater with a COD/BOD ratio below 0.30 can be considered recalcitrant. The ratio of COD/VSS and BOD/TSS were estimated at 1.49 and 1.31, respectively. The characteristics of the wastewater used in this study are similar to the PSW characteristics reported in other studies by Basitere et al. (2017).

5.3.2. Performance of the single stage anaerobic digestion

The single stage anaerobic digester was used as the primary treatment stage for organic matter and suspended solids reduction from the PSW prior to undergoing further treatment, i.e. nutrient removal. Such a set up will also ensure that the digester acts also as a biofilter. As expected, there was insignificant variations in nutrient removal observed throughout the 150 days of single stage anaerobic digestion operation. Anaerobically treated effluents generally require post-treatment in order to achieve compliance with discharge regulations pertaining to nutrient levels in the effluents intended for discharge into local fresh water bodies. Table 5.2 illustrate the single stage digester efficiency

Table 5.2: Characteristics of the single stage anaerobic digestion effluent

Parameters	Influent	Effluent	Unit	CCT Bylaw limit[a]	Removal %
Total COD	3590	1273	mg COD/L	5000	64
TSS	4413	999	mg TSS/L	1000	77
VSS	4682	744	mg VSS/L	-	84
BOD_5	3600	212	mg O_2/L	-	94
NH_3	147.5	178	mg N/L	-	-20*
PO_4^{3-}	56	63	mg P/L	25	-12.5*

aCCT: City of Cape Town wastewater and industrial effluent by-law (Cape Town, South Africa, 2014).

*Indicate accumulation within the system designed

The digester was set to operate at steady state at a mesophilic temperature (35 ˚C) at SRT of 25 days for 150 days. The COD, TSS, VSS and BOD_5 removal efficiencies reached a maximum of 64%, 77%, 84%, and 94%, respectively, at an OLR of 143.6 mg COD/L/day at the flow rate of 3590 m^3/day; whereas ammonia and phosphate slightly increased by over 12%. The slight increase in ammonia may be attributed to the degradation of proteins and amino acids present in the PSW (Krakat et al., 2017; ~~Oh, 2012~~). Figure 5.3 summarises the feed, effluent characteristics, the CCT Bylaw limit as well as the removal efficiencies of the single stage anaerobic digestion operated for 150 days at steady state.

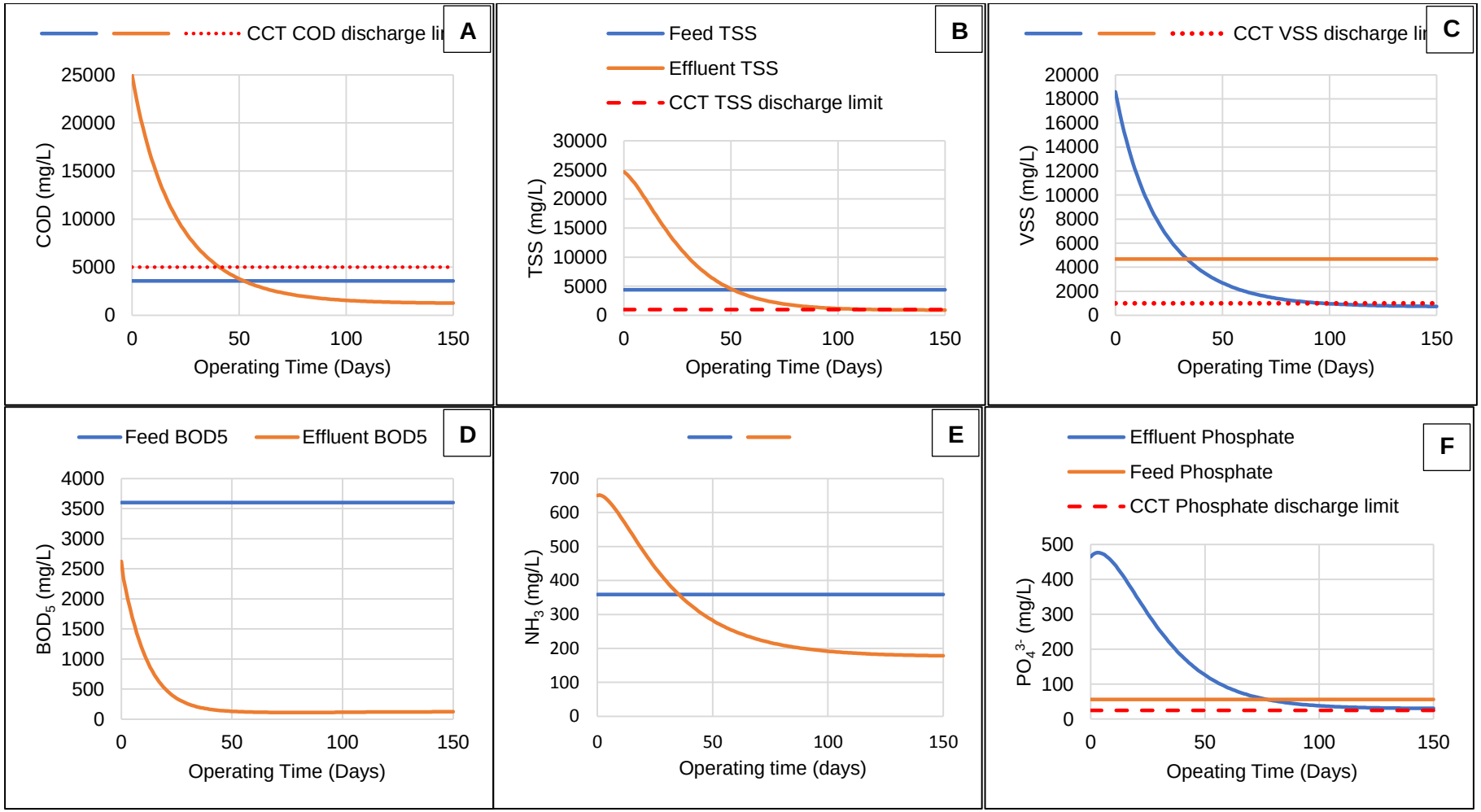

Figure 5.3: Single-stage anaerobic digestion performance – feed and effluent characterisation in relation to the CCT wastewater limits for COD, VSS, TSS, BOD5, NH_3, PO_4^{3-}.

5.3.3. Performance of the two-stage anaerobic digestion

The two-stage digestion system designed for PSW treatment was proposed in this study, i.e. using of acid-phase digestion configuration. Both digesters were set to operate at mesophilic temperature of 35 ˚C. The SRT in the first digester was 15 days and in the secondary digester was set at 25 days. Both digesters were set to operate at a pH of 7.5 which theoretically favours formative metabolism (Ghosh, 1991), which is conducive to rapid hydrolysis.

The two-stage anaerobic digestion showed better performance compared to the single-stage anaerobic digestion. The COD, TSS, VSS and BOD removal efficiencies reached a maximum of 69%, 79%, 85%, and 96%, respectively, at an at an OLR of 143.6 mg COD/L/day at the flow rate of 3590 m^3/day - see Table 5.3. The accumulation of phosphate and ammonia was observed to be minutely higher than a single stage digester. Figure 5.4 summarises the feed, effluent characteristics in comparison to the CCT Bylaw limit as well as the removal efficiencies of the two-stage anaerobic digestion operated for a period of 150 days at steady state.

Table 5.3: Characteristics of the two-stage anaerobic digestion effluent

Parameters	**Influent**	**Effluent**	**Unit**	**CCT Bylaw limit[a]**	**Removal %**
Total COD	3590	1106	mg COD/L	5000	69
TSS	4413	910	mg TSS/L	1000	79
VSS	4682	671	mgVSS/L	-	85
BOD_5	3600	122	mg O_2/L	-	96
NH_3	147.5	182	mg N/L	-	-23*
PO_4^{3-}	56	70	mg P/L	25	-25*

[a]CCT: City of Cape Town wastewater and industrial effluent by-law (Cape Town, South Africa, 2014).

*Indicate accumulation within the system designed

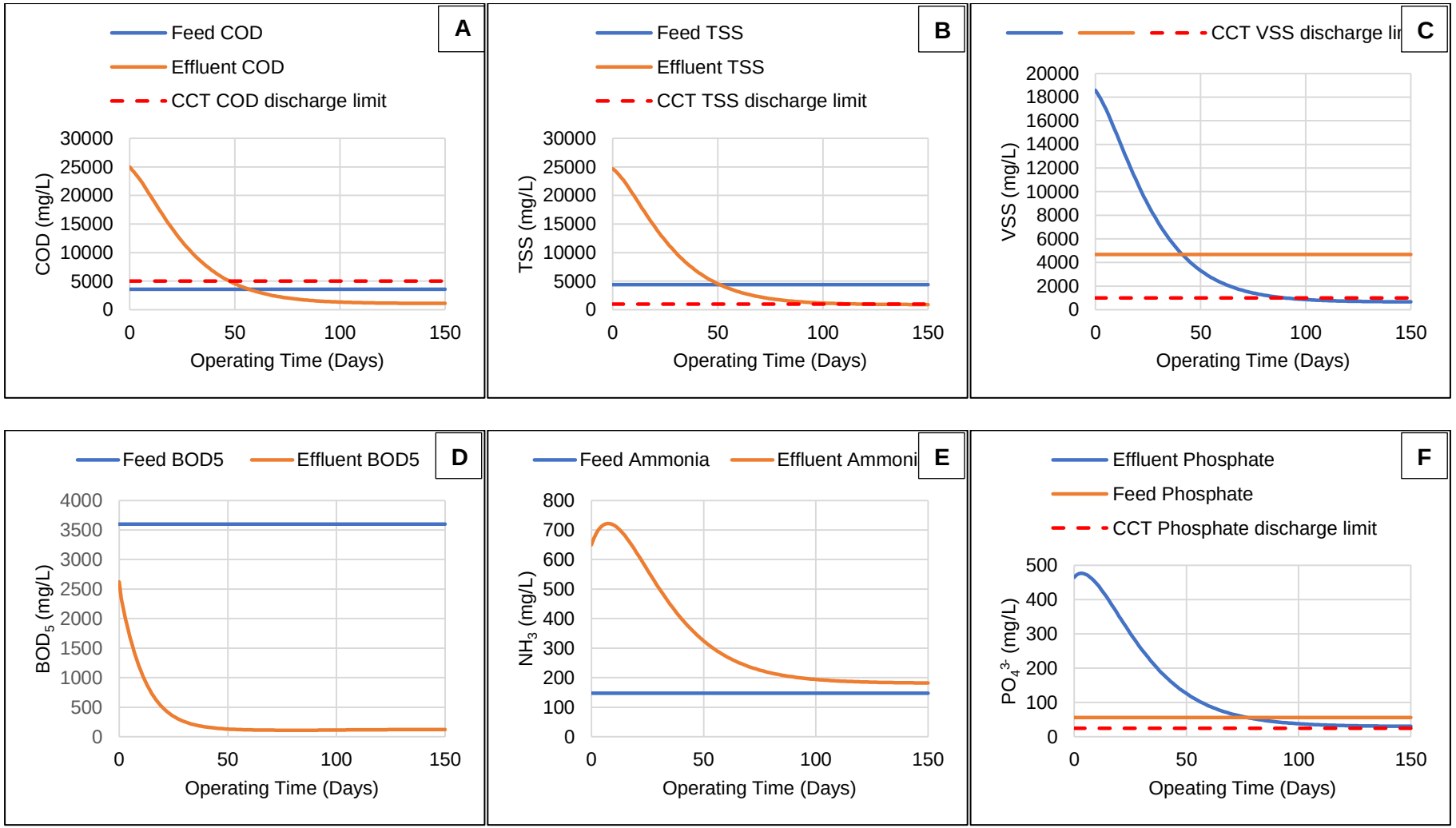

Figure 5.4: Two-stage anaerobic digestion performance – feed and effluent characterisation in relation to the CCT wastewater limits for COD, VSS, TSS, BOD5, NH_3, PO_4^{3-}.

5.3.4. Biogas production during PSW treatment

The Biogas produced from anaerobic digestion consists mainly of methane CH_4 and carbon dioxide (CO_2). The outcome from these analyses indicated that the biogas was composed of constituents highlighted in Table 5.5.

Table 5-1: Biogas production

	Biogas				
	CH_4	**O_2**	**CO_2**	**H_2**	**H_2S**
R1[a]	71%	-	27.03%	-	-
R2[b]	81%	-	18.67%	-	-

a Indicate the single stage anaerobic digestion system

b Indicate the two-stage anaerobic digestion system

It was noticed from this composition that the yield of methane was high as expected in configuration R2. As mentioned above, the first digester was set to operate at the SRT of 13 days and the second at the SRT of 25 days. This set up theoretically promotes the accumulation of solids in the second digester, thus optimizing biogas production - see Figure 5.5-5.6.

In case the biogas contains a high concentration of oxygen, it could be justified by the penetration of air through the upper part of the digester, or through the water displacement system. Such is not quantified in the model; therefore, it is important to ensure that the digester remain completely sealed during the anaerobic digestion.

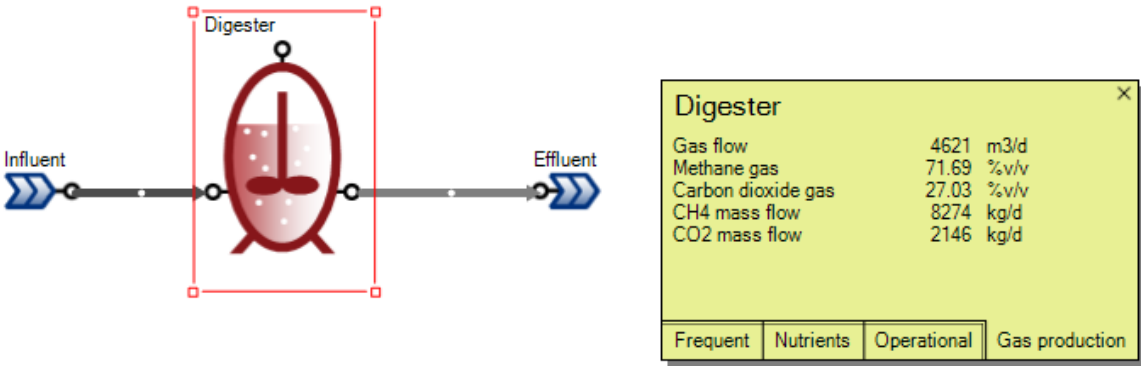

Figure 5.5: Single-stage anaerobic digestion biogas production

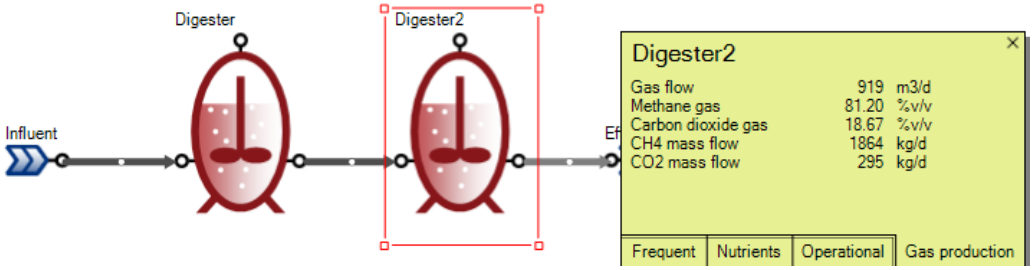

Figure 5.6: Two-stage anaerobic digestion biogas production

5.3.5. Comparison of the two designs

Although, the performance of the two-stage anaerobic digestion for the treatment of PSW showed excellent performance compared to the single stage anaerobic digestion, it was observed that the performance of the two designs was not highly differentiated - see Table 5.4, albeit configuration R2 demonstrated a higher biogas production capability. Furthermore, the absolute and relative differences between the two designs are minutely different - see Table 5.5.

Table 5.4: Selected water parameters

	COD (mg/L)	TSS (mg/L)	VSS (mg/L)	BOD_5 (mg/L)
R1[a]	64%	77%	84%	94%
R2[b]	69%	79%	85%	96%

Table 5.5: Absolute and relative difference between R1 and R2

Parameters	Designs		Absolute difference	Relative difference
	R1	R2		
COD (mg/L)	64%	69%	5%	7,81%
TSS (mg/L)	77%	79%	2%	2,60%
VSS (mg/L)	84%	85%	1%	1,2%
BOD_5 (mg/L)	94%	96%	2%	2,12%

The comparative studies were performed under similar experimental conditions and further details have been tabulated (Table 5.6) for comparative analysis with other studies. Performance of R1 and R2 were compared with the Down-Flow Expanded Granular Bed Reactor (DEGBR) and the Up flow Anaerobic Sludge Blanket Reactor (UASB) reactor from the other studies.

Table 5.6: Comparison of performance between high-rate anaerobic reactors and the designed anaerobic digesters

Reactor	Temperature, ºC	OLR	Feed type	COD removal %	Reference
R1	**35**	**143.6 mg/L/day**	**Poultry slaughterhouse wastewater**	**64**	**This study**
R2	**35**	**143.6 mg/L/day**	**Poultry slaughterhouse wastewater**	**69**	**This study**
DEGBR	35	148.69 mg/L/hr	Poultry slaughterhouse wastewater	95	Njoya (2017)
UASB	35	12.5 kg/m^3/day	Acetic acid and Glucose	90	Jhung and Choi (1995)
UASB	23	2.5 kg/m^3/day	Poultry slaughterhouse wastewater	43	Del Nery et al. (2008)

CHAPTER 6

CONCLUSION AND RECOMMENDATIONS

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6.1. Conclusion

The following conclusions were drawn based on the results of this study:

Both the single-stage and two-stage anaerobic digestion proposed model operated at steady state for 150 days were able to consistently reduce the organic matter and suspended solids content of the pre-filtered PSW throughout its 150 days of operation. The single stage anaerobic digestion system was set to operate under mesophilic temperature (35 ˚C) with a solid retention time (SRT) of 25 days.

Moreover, the evaluation of the performance of the single stage anaerobic digestion for the treatment of PSW was executed at a flow rate of 3590 m^3/day, with the result that the digester designed showed excellent performance in the removal of organic matter from the PSW, with average percentage removal 64%, 77%, 84%, and 94% for the tCOD, TSS, VSS BOD_5, respectively, at an organic load rate (OLR) of 143.6 mg COD/L/day. As for the two-stage anaerobic digestion system, the tCOD, TSS, VSS and BOD_5 removal efficiencies reached a maximum of 69%, 79%, 85%, and 96%, respectively, at an organic load rate (OLR) of 143.6 mg COD/L/day at the same flow rate.

For both designed models, a minute accumulation in ammonia (NH_3) and phosphate (PO_4^{3-}) was observed. Thus, post-treatment with regard to PO^{3-}_4, NH_3 removal is required in order to meet the CCT wastewater and industrial effluent by-law limits.

Although the two-stage anaerobic digestion demonstrated adequate performance, it was concluded that the single-stage anaerobic digestion is the process recommended for PSW treatment, because it is less costly with relative low performance difference, and the suitability adoption by for small scale poultry product producers, unless biogas production is the primary goal than PSW treatment.

The PSW treatment systems designed for this study were successfully employed with the resultant effluent being compliant with the CCT wastewater and industrial effluent by-law limits. Although, both the PO^{3-}_4 and NH_3 require further monitoring and tertiary system design for the removal. Therefore, the poultry slaughterhouse from which the PSW was obtained will be able to be safely discharged into municipal wastewater treatment work if the designs proposed herein are adopted; however, the treated PSW will not be suitable for re-use.

6.2. Recommendations

The following recommendations are suggested for further research:

- Further studies should include recirculation of a portion of the effluent in the system in the two-stage anaerobic digestion for dilution of the feed and to simulate the performance of such an unusual design in the Sumo modelling software.
- Consideration in calibrating the model to an existing working digester and assess if the empirical kinetic and stoichiometric values are representing digester performance, will greatly enhance the simulator predictability of PSW treatment.
- Further research should consider performing a dynamic simulation and assessment how the model responds at different SRTs and HRTs.
- Further research may consider additional post-treatment processes for the removal of PO_4^{3-} and NH_3.

CHAPTER 7

REFERENCES

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Adeyemo, O.K., Ayodeji, I.O. and Aika-Raji, C.O., 2002. The water quality and sanitary conditions in a major abattoir (Bodija) in Ibadan, Nigeria. African Journal of Biomedical Research, 5(1-2). pp.53-55.

Al-Ghouti, M.A., Khraisheh, M.A.M., Allen, S.J. and Ahmad, M.N., 2003. The removal of dyes from textile wastewater: a study of the physical characteristics and adsorption mechanisms of diatomaceous earth. Journal of Environmental Management, 69(3), pp.229-238.

Anderson, G.K., Kasapgil, B. and Ince, O., 1994. Microbiological study of two-stage anaerobic digestion during start-up. Water Research, 28(11), pp.2383-2392.

Barbut, S. 2015. The Science of Poultry and Meat Processing. University of Guelph, Ontario.

Basitere, M., Rinquest, Z., Njoya, M., Sheldon, M.S. and 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.

Basitere, M., Williams, Y., Sheldon, M.S., Ntwampe, S.K.O., De Jager, D. and 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 and Technology, 11(1), pp.86-92.

Batstone, D.J., Keller, J., Angelidaki, I., Kalyuzhnyi, S.V., Pavlostathis, S.G., Rozzi, A., Sanders, W.T.M., Siegrist, H. and Vavilin, V.A., 2002. The IWA anaerobic digestion model no 1 (ADM1). Water Science and Technology, 45(10), pp.65-73.

Boubaker, F. and Ridha, B.C., 2008. Modelling of the mesophilic anaerobic co-digestion of olive mill wastewater with olive mill solid waste using anaerobic digestion model No. 1 (ADM1). Bioresource technology, 99(14), pp.6565-6577.

Boopathy, R., 2000. Factors limiting bioremediation technologies. Bioresource technology, 74(1), pp.63-67.

Blumensaat, F. and Keller, J., 2005. Modelling of two-stage anaerobic digestion using the IWA Anaerobic Digestion Model No. 1 (ADM1). Water Research, 39(1), pp.171-183.

Bustillo-Lecompte, C. F., Ghafoori, S. & Mehrvar, M. 2016. Photochemical degradation of an actual slaughterhouse wastewater by continuous UV/H_2O_2 photoreactor with recycle. Journal of Environmental Chemical Engineering, 4, 719-732.

Bustillo-Lecompte, C., Mehrvar, M. and Quiñones-Bolaños, E., 2016. Slaughterhouse wastewater characterization and treatment: an economic and public health necessity of the meat processing industry in Ontario, Canada. Journal of Geoscience and Environment Protection, 4(04), p.175.

Bustillo-Lecompte, C. F. & Mehrvar, M. 2015a. Slaughterhouse wastewater characteristics, treatment, and management in the meat processing industry: a review on trends and advances. Journal of Environmental Management, 161, 287-302.

Bustillo-Lecompte, C. F., Mehrvar, M. & Quiñones-Bolaños, E. 2014. Cost-effectiveness analysis of TOC removal from slaughterhouse wastewater using combined anaerobic–aerobic and UV/H_2O_2 processes. Journal of Environmental Management, 134, 145-152.

Bus, S., Yetilmezsoy, K. & Kocak, E. 2009. Anaerobic digestion technology in poultry and livestock waste treatment—a literature review. Waste Management & Research, 27, 3-18.

Canencia, O. P., Dalugdug, M. D., Emano, A. M. B., Mendoza, R. C. & Walag, A. M. P. 2016. Slaughter waste effluents and river catchment watershed contamination in Cagayan de Oro City, Philippines. Journal of Biodiversity and Environmental Sciences, 9, 142-148.

Cao, W. & Mehrvar, M. 2011. Slaughterhouse wastewater treatment by combined anaerobic baffled reactor and UV/H_2O_2 processes. Chemical Engineering Research and Design, 89, 1136-1143.

Cheremisinoff, P., 1997. Handbook of engineering polymeric materials. CRC Press.

City of Cape Town. 2006. Wastewater and industrial effluent bylaw, 2016. http://www.samfa.org.za/Library/WasteWaterLaws/CTWasteWaterByLaw.pdf. Accessed date: 12/11/2018

Cohen, A., Zoetemeyer, R.J., Van Deursen, A. and Van Andel, J.G., 1979. Anaerobic digestion of glucose with separated acid production and methane formation. Water Research, 13(7), pp.571-580.

Copp, J.B., Jeppsson, U. and Rosen, C., 2003. Towards an ASM1–ADM1 state variable interface for plant-wide wastewater treatment modeling. Proceedings of the water environment federation, 2003(7), pp.498-510.

Coskun, T., Debik, E., Kabuk, H. A., Manav Demir, N., Basturk, I., Yildirim, B., Temizel, D. & Kucuk, S. 2016. Treatment of poultry slaughterhouse wastewater using a membrane process, water reuse, and economic analysis. Desalination and Water Treatment, 57, 4944-4951.

Debik, E. and Coskun, T.J.B.T., 2009. Use of the Static Granular Bed Reactor (SGBR) with anaerobic sludge to treat poultry slaughterhouse wastewater and kinetic modeling. *Bioresource Technology*, *100*(11), pp.2777-2782.

Del Nery, V., Damianovic, M.H.Z. and Barros, F.G., 2001. The use of upflow anaerobic sludge blanket reactors in the treatment of poultry slaughterhouse wastewater. Water Science and Technology, 44(4), pp.83-88.

Del Nery, V., Pozzi, E., Damianovic, M.H., Domingues, M.R. and Zaiat, M., 2008. Granules characteristics in the vertical profile of a full-scale upflow anaerobic sludge blanket reactor treating poultry slaughterhouse wastewater. Bioresource technology, 99(6), pp.2018-2024.

Dendooven, L. & Escamilla-Silva, E. 2005. Poultry slaughter wastewater treatment with an up-flow anaerobic sludge blanket (UASB) reactor. Bioresource Technology, 96, 1730-1736.

Department of Water Affairs and Forestry (DWAF), 1996. Department of Water Affairs and Forestry (DWAF)(second edition), South African Water Quality Guidelines, Volume 1, Domestic Use. Department of Water Affairs and Forestry, Pretoria, South Africa.

Derbal, K., Bencheikh-Lehocine, M., Cecchi, F., Meniai, A.H. and Pavan, P., 2009. Application of the IWA ADM1 model to simulate anaerobic co-digestion of organic waste with waste activated sludge in mesophilic condition. Bioresource Technology, 100(4), pp.1539-1543.

Dold, P.L. and Marais, G.V.R., 1986. Evaluation of the general activated sludge model proposed by the IAWPRC task group. Water Science and Technology, 18(6), pp.63-89.

Ekama, G.A. and Marais, G., 1977. The activated sludge process. Part II–dynamic behaviour. Water SA, 3(1), pp.18-50.

Evans, E.A., Ellis, T.G., Gullicks, H. and Ringelestein, J., 2004. Trickling filter nitrification performance characteristics and potential of a full-scale municipal wastewater treatment facility. Journal of Environmental Engineering, 130(11), pp.1280-1288.

Eze, C. N. & Eze, P. C. 2018. Effect of abattoir waste on the physicochemical and bacteriological qualities of new-artisan river in Enugu, Nigeria. Nigerian Journal of Technology, 37, 262.

Goel, P. K . 2006. Water pollution: causes, effects and control. New Age International. pp. 201-215

Ghosh, S., 1991. Pilot-scale demonstration of two-phase anaerobic digestion of activated sludge. Water Science and Technology, 23(7-9), pp.1179-1188.

Edition, F., 2011. Guidelines for drinking-water quality. WHO chronicle, 38(4), pp.104-8.

Henze, M., Gujer, W., Mino, T. & Van Loosdrecht, M. 2000. Activated sludge models ASM1, ASM2, ASM2d and ASM3, IWA publishing. pp. 45-70

Henze, M., Van Loosdrecht, M.C., Ekama, G.A. And Brdjanovic, D. Eds., 2008. Biological wastewater treatment. IWA publishing. pp.65-80

Henze, M., Gujer, W., Mino, T., Matsuo, T., Wentzel, M.C., Marais, G.V.R. and Van Loosdrecht, M.C., 1999. Activated sludge model no. 2d, ASM2d. Water Science and Technology, 39(1), pp.165-182.

Igoni, A.H., Ayotamuno, M.J., Eze, C.L., Ogaji, S.O.T. And Probert, S.D., 2008. Designs of anaerobic digesters for producing biogas from municipal solid-waste. Applied Energy, 85(6), pp.430-438.

Jhung, J.K. and Choi, E., 1995. A comparative study of UASB and anaerobic fixed film reactors with development of sludge granulation. Water Research, 29(1), pp.271-277.

Judd, S., 2010. The MBR book: principles and applications of membrane bioreactors for water and wastewater treatment. Elsevier.

Kothari, C. R. 2004. Research methodology: Methods and techniques, New Age International.

Kato, M.T., Field, J.A., Versteeg, P. and Lettinga, G., 1994. Feasibility of expanded granular sludge bed reactors for the anaerobic treatment of low-strength soluble wastewaters. Biotechnology and Bioengineering, 44(4), pp.469-479.

Karakashev, D., Batstone, D.J., Trably, E. and Angelidaki, I., 2006. Acetate oxidation is the dominant methanogenic pathway from acetate in the absence of Methanosaetaceae. Applied and Environmental Microbiology, 72(7), pp.5138-5141.

Krakat, N., Demirel, B., Anjum, R. and Dietz, D., 2017. Methods of ammonia removal in anaerobic digestion: a review. Water Sccience and Technollogy, 76(8), pp.1925-1938.

Koch, G., Kühni, M., Gujer, W. and Siegrist, H., 2000. Calibration and validation of activated sludge model no. 3 for Swiss municipal wastewater. Water Research, 34(14), pp.3580-3590.

Mach, K.F. and Ellis, T.G., 2000. Performance characteristics of the static granular bed reactor. Proceedings of the Water Environment Federation, 2000(11), pp.764-781.

Mamais, D., Jenkins, D. and Prrr, P., 1993. A rapid physical-chemical method for the determination of readily biodegradable soluble COD in municipal wastewater. *Water* Research, 27(1), pp.195-197.

Mao, C., Feng, Y., Wang, X. and Ren, G., 2015. Review on research achievements of biogas from anaerobic digestion. Renewable and Sustainable Energy Reviews, 45, pp.540-555.

Marais, G. and Ekama, G.A., 1976. The activated sludge process part I-steady state behaviour. Water sA, 2(4), pp.164-200.

Melcer, H., 2004. Methods for wastewater characterization in activated sludge modelling. IWA publishing.

Molapo, N.A., 2009. Waste handling practices in the South African high-throughput poultry abattoirs (Doctoral dissertation, Bloemfontein: Central University of Technology, Free State).

Metcalf, E. 2003. *Wastewater Engineering: Treatment and Reuse*. 4th ed. New York: McGraw-Hill.

Muha, I., Zielonka, S., Lemmer, A., Schönberg, M., Linke, B., Grillo, A. and Wittum, G., 2013. Do two-phase biogas plants separate anaerobic digestion phases?–A mathematical model for the distribution of anaerobic digestion phases among reactor stages. Bioresource Technology, 132, pp.414-418.

Njoya, M., 2017. Reactor reconfiguration for enhanced performance of a down-flow expanded granular bed reactor (DEGBR) for poultry slaughterhouse treatment (Master dissertation, Cape Peninsula University of Technology).

Ojekunle, O.Z. and Lateef, S.T., 2017. environmental impact of abattoir waste discharge on the quality of surface water and ground water in abeokuta. journal of environmental and Analytical Toxicology, 7(509), pp.2161-0525.

Orhon, D. and Çokgör, E.U., 1997. COD fractionation in wastewater characterization—the state of the art. Journal of Chemical Technology & Biotechnology: International Research in Process, Environmental and Clean Technology, 68(3), pp.283-293.

Ostrem, K.M., Millrath, K. and Themelis, N.J., 2004, January. Combining anaerobic digestion and waste-to-energy. In 12th Annual North American Waste-to-Energy Conference (pp. 265-271). American Society of Mechanical Engineers.

Pina, S., Buti, M., Cotrina, M., Piella, J. & Girones, R. 2000. HEV identified in serum from humans with acute hepatitis and in sewage of animal origin in Spain. Journal of Hepatology, 33, 826-833.

Rajeshwari, K.V., Balakrishnan, M., Kansal, A., Lata, K. and Kishore, V.V.N., 2000. State-of-the-art of anaerobic digestion technology for industrial wastewater treatment. Renewable and Sustainable Energy Reviews, 4(2), pp.135-156.

Rinquest, Z., 2017. Poultry slaughterhouse wastewater treatment using a static granular bed reactor (SGBR) coupled with a hybrid sidestream membrane bioreactor (Master dissertation, Cape Peninsula University of Technology).

Salminen, E. and Rintala, J., 2002. Anaerobic digestion of organic solid poultry slaughterhouse waste–a review. Bioresource technology, 83(1), pp.13-26.

Schmidt, J.E. and Ahring, B.K., 1996. Granular sludge formation in upflow anaerobic sludge blanket (UASB) reactors. *Biotechnology and bioengineering*, *49*(3), pp.229-246.

Schober, G., Schäfer, J., Schmid-Staiger, U. and Trösch, W., 1999. One and two-stage digestion of solid organic waste. Water Research, 33(3), pp.854-860.

Song, T., Li, S., Ding, W., Li, H., Bao, M. and Li, Y., 2018. Biodegradation of hydrolyzed polyacrylamide by the combined expanded granular sludge bed reactor-aerobic biofilm reactor biosystem and key microorganisms involved in this bioprocess. *Bioresource technology*, *263*, pp.153-162.

South Africa. 1998. National Water Act, No 36 of 1998. http://www.dwa.gov.za/Documents/Legislature/nw_act/NWA.pdf. Accessed date: 10/10/2018

South Africa. 1997. Water Services Act, No 108 of 1997. http://www.dwaf.gov.za/Documents/Legislature/a108-97.pdf. Accessed date: 10/09/2018

Seghezzo, L., Zeeman, G., Van Lier, J. B., Hamelers, H. & Lettinga, G. 1998. A review: the anaerobic treatment of sewage in UASB and EGSB reactors. Bioresource Technology, 65, 175-190.

Siegrist, H., Renggli, D. and Gujer, W., 1993. Mathematical modelling of anaerobic mesophilic sewage sludge treatment. Water Science and Technology, 27(2), pp.25-36.

Sivagurunathan, P., Kumar, G., Bakonyi, P., Kim, S.H., Kobayashi, T., Xu, K.Q., Lakner, G., Tóth, G., Nemestóthy, N. and Bélafi-Bakó, K., 2016. A critical review on issues and overcoming strategies for the enhancement of dark fermentative hydrogen production in continuous systems. International Journal of Hydrogen Energy, 41(6), pp.3820-3836.

Stets, M., Etto, R., Galvão, C., Ayub, R., Cruz, L., Steffens, M. & Barana, A. 2014. Microbial community and performance of slaughterhouse wastewater treatment filters. Genetics and Molecular Research, 13, 4444-4455.

Tawfik, A., Sobhey, M. and Badawy, M., 2008. Treatment of a combined dairy and domestic wastewater in an up-flow anaerobic sludge blanket (UASB) reactor followed by activated sludge (AS system). Desalination, 227(1-3), pp.167-177.

Whitman, W.G., 1923. The two-film theory of gas absorption. **Chemical** and Metallurgical ., 29, pp.146-148.

Verheijen, L., Wiersema, D. & Hulshoff Pol, L. 1996. Livestock and the Environment–Finding a Balance. Management of Waste from Animal Product Processing. Coordinated by the FAO, USAID and World Bank.

Von Sperling, M. 2017. Wastewater characteristics, treatment and disposal, IWA publishing.

Weber, T. J. 2007. Wastewater treatment. Metal Finishing, 105, 699-714.

Wentzel, M.C., Mbewe, A. and Ekama, G.A., 1995. Batch test for measurement of readily biodegradable COD and active organism concentrations in municipal waste waters. WATER SA-PRETORIA-, 21, pp.117-117.

Youn, S. Y., Jeong, O. M., Choi, B. K., Jung, S. C. & Kang, M. S. 2017. Comparison of the antimicrobial and sanitizer resistance of Salmonella isolates from chicken slaughter processes in Korea. Journal of Food Science, 82, 711-717.

Zahller, J.D., Bucher, R.H., Ferguson, J.F. and Stensel, H.D., 2007. Performance and stability of two-stage anaerobic digestion. Water environment research, 79(5), pp.488-497.

APPENDICES

Appendix A: Model overview

Table A-1: Key parameters

Symbol	Name	Value	Unit
µNITO	Maximum specific growth rate of nitrifiers	0,9	1/d
KNHx,NITO,AS	Ammonia half saturation for NITOs	0,7	g N/m3
µOHO	Maximum specific growth rate of OHOs	4	1/d
KSB,AS	Substrate half saturation for OHOs	5	g COD/m3
KO2,OHO,AS	O2 half saturation for OHOs	0,05	g O2/m3
µPAO	Maximum specific growth rate of PAOs	0,9	1/d
KPO4,PAO,AS	PO4 half saturation for PAOs	0,3	g P/m3
qHYD	Hydrolysis rate coefficient	2	1/d

Table A-2: Methylotroph kinetics

Symbol	Name	Value	Unit
µMEOLO	Methylotroph maximum specific growth rate	1,3	1/d
KMEOL,AS	Methanol half saturation coefficient	0,5	g COD/m3
KO2,MEOLO,AS	O2 half saturation for MEOLOs	0,05	g O2/m3
KNO3,MEOLO,AS	NOx half saturation for MEOLOs	0,03	g N/m3
bMEOLO	Aerobic decay rate coefficient for methylotrophs	0,05	1/d
qMEOL	Methanol degradation rate in anaerobic environments	10	1/d

Table A-3: Heterotrophic kinetics

Symbol	Name	Value	Unit
µOHO	Maximum specific growth rate of OHOs	4	1/d
KSB,AS	Substrate half saturation for OHOs	5	g COD/m3
KO2,OHO,AS	O2 half saturation for OHOs	0,05	g O2/m3
KVFA,AS	VFA half saturation for OHOs	0,5	g COD/m3
KMEOL,OHO,AS	Methanol half saturation for OHOs (aerobic)	0,1	g COD/m3
KNO3,OHO,AS	NOx half saturation for OHOs	0,03	g N/m3
ηOHO,anox	Anoxic growth reduction for OHOs	0,6	
bOHO	Aerobic decay rate coefficient for OHOs	0,62	1/d
µFERM,OHO	Fermentation rate coefficient	0,4	1/d
KSB,ana,AS	Substrate half saturation during fermentation	5	g COD/m3

Table A-4: Hydrogenotrophic methanogen kinetics

Symbol	Name	Value	Unit
µHMETO	Maximum specific growth rate of HMETO	1,3	1/d
KH2,HMETO,AS	H2 half saturation for HMETO	0,1	g COD/m3
KO2,HMETO,AS	Oxygen half saturation for HMETO	0,05	g O2/m3
KNO3,HMETO,AS	NOx half saturation for HMETO	0,05	g N/m3
bHMETO	Decay rate for HMETO (aerobic)	0,13	1/d
pHlow,HMETO	pH inhibition - low value	5,5	pHunit
pHhigh,HMETO	pH inhibition - high value	9,5	pHunit

Table A-5: Phosphate-Accumulating Organisms kinetics

Symbol	Name	Value	Unit
µPAO	Maximum specific growth rate of PAOs	0,9	1/d
KPO4,PAO,AS	PO4 half saturation for PAOs	0,3	g P/m3
µPAO,lim	Maximum specific growth rate of PAOs, P limited	0,49	1/d
KPHA,AS	PHA half saturation coefficient	0,1	g COD/m3
KO2,PAO,AS	Oxygen half saturation for PAOs	0,05	g O2/m3
KNO3,PAO,AS	NOx half saturation for PAOs	0,03	g N/m3
ηPAO,anox	PAO anoxic growth factor	0,33	
bPAO	Aerobic decay rate coefficient for PAOs	0,05	1/d
bPPLO,ana	Anaerobic maintenance PP cleavage	0,03	1/d
qPAO,PHA	PHA storage rate	2	1/d
KSTO,VFA,AS	VFA half saturation for storage	5	g COD/m3
KPPLO,AS	PP-low half saturation for storage	0,01	g P/m3
KMg,PAO,AS	Mg limitation for PP storage (counter-ion)	0,001	g Mg/m3
KK,PAO,AS	K limitation for PP storage (counter-ion)	0,001	g K/m3
KCa,PAO,AS	Ca limitation for PP storage (counter-ion)	0,001	g Ca/m3
KPP,lim,AS	PP limitation as nutrient	0,002	g P/m3
KPO4,lim,AS	PO4 limitation as nutrient	0,005	g P/m3

Table A-6: Parameters for half saturation coefficients in biofilms

Symbol	Name	Value	Unit
fKS,biofilm	Diffusion factor for half saturation coefficients	0.1	-

Table A-7: Nitrifiers kinetics

Symbol	Name	Value	Unit
µNITO	Maximum specific growth rate of nitrifiers	0,9	1/d
KNHx,NITO,AS	Ammonia half saturation for NITOs	0,7	g N/m3
KCO2,NITO,AS	CO2 half saturation for NITOs	44	g TIC/m3
KCO2,NITO,sidestream	CO2 half saturation for NITOs	176	g TIC/m3
KCO2,NITO,pH,AS	HCO3- half saturation for NITOs	1	mmol [HCO3-]/L
KCO2,NITO,pH,sidestream	HCO3- half saturation for NITOs	4	mmol [HCO3-]/L
KO2,NITO,AS	Oxygen half saturation for NITOs	0,25	g O2/m3
KO2,NITO,sidestream	Oxygen half saturation for NITOs	0,5	g O2/m3
KNO3,NITO,AS	Half saturation for anoxic conditions for NITOs	0,03	g N/m3
bNITO	Aerobic decay rate coefficient for NITOs	0,17	1/d
KNH3,NITO,AS	Free ammonia half saturation for NITOs	9999000	mmol/L
KNH3,NITO,pH,AS	Ammonium half saturation for NITOs	9999	g N/m3

Table A-8: Volatile Fatty Acid (Acido) clastic methanogen kinetics

Symbol	Name	Value	Unit
µAMETO	Maximum specific growth rate of AMETO	0,3	1/d
KVFA,AMETO,AS	VFA Haldane half saturation for AMETO	400	g COD/m3
KVFA,INH,AMETO,AS	VFA Haldane inhibition for AMETO	99999	g COD/m3
KO2,AMETO,AS	Oxygen half saturation for AMETO	0,05	g O2/m3
KNO3,AMETO,AS	NOx half saturation for AMETO	0,05	g N/m3
bAMETO	Decay rate for AMETO (aerobic)	0,03	1/d
KNHx,AMETO,pH,AS	NHx non-competitive inhibition AMETO	2500	g N/m3
KNH3,AMETO,pH,AS	NH3 non-competitive inhibition AMETO	24	mmol/L
pHlow,AMETO	pH inhibition - low value	5,5	pHunit
pHhigh,AMETO	pH inhibition - high value	9,5	pHunit

Table A-9: Precipitation kinetics

Symbol	Name	Value	Unit
qCaCO3,PREC	CaCO3 precipitation rate parameter	0	g.m-3.d-1
qCaCO3,DISS	CaCO3 redissolution rate parameter	0	g.m-3.d-1
qSTR,PREC	Struvite precipitation rate parameter	10	g.m-3.d-1
qSTR,DISS	Struvite dissolution rate parameter	1	g.m-3.d-1
qACP,PREC	ACP precipitation rate	0	g.m-3.d-1
qACP,DISS	ACP dissolution rate	0	g.m-3.d-1
qVivi,PREC	Vivianite precipitation rate parameter	0,01	g.m-3.d-1
qVivi,DISS	Vivianite dissolution rate parameter	0,001	g.m-3.d-1
KSTR,INH,DISS	Inhibition coefficient for STR redissolution	0,01	g TSS/m3
KACP,INH,DISS	Inhibition coefficient for ACP redissolution	0,01	g TSS/m3
KCaCO3,INH,DISS	Inhibition coefficient for CaCO3 redissolution	0,01	g TSS/m3
KVivi,INH,DISS	Inhibition coefficient for Vivi redissolution	0,01	g TSS/m3

Table A-10: Parameters for gas transfer

Symbol	Name	Value	Unit
fkLaN2	Nitrogen mass transfer parameter	100	%
fkLaCO2	Carbon dioxide mass transfer parameter	100	%
fkLaCH4	Methane mass transfer parameter	100	%
fkLaH2	Hydrogen mass transfer parameter	100	%
fkLaNH3	Ammonia mass transfer parameter	0	%
fkLaO2	Oxygen mass transfer parameter	100	%

Table A-11: Hydrous Ferric Oxides kinetics

Symbol	Name	Value	Unit
qHFOH,AGING	Aging coefficient for XHFO,H	450	1/d
qHFOL,AGING	Aging coefficient for XHFO,L	0,1	1/d
qP,COPREC	Maximum P binding and coprecipitation rate on XHFO,H	360	1/d
qP,BIND	Maximum P binding rate on XHFO,L	0,3	1/d
qHFOH,DISS	Redissolution rate coefficient - XHFO,H,P	36	1/d
qHFOL,DISS	Redissolution rate coefficient - XHFO,L,P	36	1/d
qHFO,RED	HFO (ferric) reduction rate	2	1/d
qFe,OX	Ferrous oxidation rate	1	1/d
KP,DISS	Inhibition coefficient for SPO4 for redissolution	0,03	g P/m3
KP,BIND	Half saturation coefficient for SPO4	0,1	g P/m3

Table A-12: Diffusion coefficients - colloidal compounds

Symbol	Name	Value	Unit
DCB	Diffusion coefficient of colloidal biodegradable substrate	0.000025	cm2.s-1
DCU	Diffusion coefficient of colloidal unbiodegradable organics	0.000025	cm2.s-1

Table A-13: Hydrous Ferric Oxides stoichiometry

Symbol	Name	Value	Unit
ASFH	Active site factor for HFOH	1,2	mol P.mol Fe-1
ASFL	Active site factor for HFOL	0,6	mol P.mol Fe-1

Table A-14: Common switches

Symbol	Name	Value	Unit
KNHx,BIO,AS	NHx half saturation for biomasses	0,005	g N/m3
KPO4,BIO,AS	PO4 half saturation for biomasses	0,002	g P/m3
KCO2,BIO,AS	CO2 half saturation for autotrophs (except NITO)	4,4	g TIC/m3
ηb,anox	Anoxic reduction for decay	0,5	
ηb,ana	Anaerobic reduction for decay	0,1	
ηHYD,anox	Anoxic reduction for hydrolysis	0,5	
ηHYD,ana	Anaerobic reduction for hydrolysis	0,5	
mtox,anox	Anoxic increasing factor for decay of anaerobs	5	
mtox,aer	Aerobic increasing factor for decay of anaerobs	10	
mtox,ana,max	Anaerobic increasing factor for decay of aerobs	10	
KCAT,AS	Sodium half saturation for synthesis inorganics	0,1	g/m3
KAN,AS	Choride half saturation for synthesis inorganics	0,1	g/m3
pHlow	pH inhibition - low value	3	pHunit
pHhigh	pH inhibition - high value	11	pHunit

Table A-15: Conversion kinetics

Symbol	Name	Value	Unit
qHYD	Hydrolysis rate coefficient	2	1/d
qFLOC	Flocculation rate coefficient	50	1/d
KFLOC,AS	Flocculation half saturation coefficient	0,001	g COD/m3
KHYD,AS	Hydrolysis half saturation coefficient	0,05	g COD/m3
qAMMON	Ammonification rate coefficient	0,05	1/d
qSPB	Phosphate release rate coefficient	0,5	1/d
qXE	Endogenous residue conversion rate coefficient	0,007	1/d
qASSIM	Assimilative nutrient production rate coefficient	1	1/d
KNHx,ASSIM,AS	Assimilative NHx half saturation	0,0005	g N/m3
KNOx,ASSIM,AS	Assimilative NO3 half saturation	0,001	g N/m3
KOHO,ASSIM,AS	Assimilative OHO half saturation	0,001	g COD/m3
KCO2,ASSIM,AS	Assimilative CO2 half saturation	5	g TIC/m3

Table A-16: Temperature dependency

Symbol	Name	Value	Unit
θμ,OHO	Arrhenius coefficient for OHO growth	1,04	
θFERM,OHO	Arrhenius coefficient for fermentation (OHO)	1,04	
θb,OHO	Arrhenius coefficient for OHO decay	1,03	
θμ,MEOLO	Arrhenius coefficient for MEOLO growth	1,06	
θb,MEOLO	Arrhenius coefficient for MEOLO decay	1,03	
θμ,PAO	Arrhenius coefficient for PAO growth	1,04	
θμ,PAO,lim	Arrhenius coefficient for PAO growth (P limited)	1,04	
θq,PAO,PHA	Arrhenius coefficient for PHA storage	1,04	
θb,PAO	Arrhenius coefficient for PAO decay	1,03	
θb,PPLO,ana	Arrhenius coefficient for anaerobic PP storage	1,03	
θμ,NITO	Arrhenius coefficient for NITO growth	1,072	
θb,NITO	Arrhenius coefficient for NITO decay	1,03	
θμ,AMETO	Arrhenius coefficient for AMETO growth	1,03	
θb,AMETO	Arrhenius coefficient for AMETO decay	1,03	
θμ,HMETO	Arrhenius coefficient for HMETO growth	1,03	
θb,HMETO	Arrhenius coefficient for HMETO decay	1,03	
θq,FLOC	Arrhenius coefficient for flocculation	1	
θq,HYD	Arrhenius coefficient for hydrolysis	1	
θq,AMMON	Arrhenius coefficient for ammonification	1	
θq,SPB	Arrhenius coefficient for PO4 conversion	1	
θq,XE	Arrhenius coefficient endogenous residual conversion	1	
θq,ASSIM	Arrhenius coefficient assimilative kinetics	1	
θq,Fe,OX	Arrhenius coefficient for ferrous iron oxidation kinetics	1,04	
θq,HFO,RED	Arrhenius coefficient for ferric iron reduction kinetics	1,04	
Tbase	Arrhenius base temperature	20	Co

Table A-17: Stoichiometric yields

Symbol	Name	Value	Unit
YOHO,VFA,ox	Aerobic yield of OHOs on VFA	0,6	g XOHO. g SVFA-1
YOHO,VFA,anox	Anoxic yield of OHOs on VFA	0,45	g XOHO. g SVFA-1
YOHO,SB,ox	Aerobic yield of OHOs on substrate	0,67	g XOHO. g SB-1
YOHO,SB,anox	Anoxic yield of OHOs on substrate	0,54	g XOHO. g SB-1
YOHO,SB,ana	Anaerobic yield of OHOs on substrate	0,1	g XOHO. g SB-1
YOHO,H2,ana	Anaerobic yield of H2 production in fermentation	0,35	g XOHO. g SB-1
YOHO,SMEOL,ox	Aerobic yield of OHOs on methanol	0,4	g XOHO. g SMEOL-1
YMEOLO	MEOLO yield	0,4	g XMEOLO. g SMEOL-1
frCH,SB	Carbohydrate fraction in SB	1	
frPROT,SB	Carbohydrate fraction in SB	0	
YPAO,PHA,ox	Aerobic yield of PAOs on PHA	0,639	g XPAO.g XPHA-1
YPAO,PHA,anox	Anoxic yield of PAOs on PHA	0,52	g XPAO.g XPHA-1
YPPLO	PPlow yield on PP storage (rest goes to PPhigh)	0,94	g XPP,LO.g SPO4-1
fPHA,PP,ox	PHA to PP ratio, aerobic	0,95	g XPHA.g XPP-1
fPHA,PP,anox	PHA to PP ratio, anoxic	0,35	g XPHA.g XPP-1
fP,VFA	P release to VFA ratio	0,49	
iTSS,PP	TSS content of PP	3,516129032	g XPP.g XTSS-1
YNITO	NITO yield	0,24	g XNITO. g SNHx-1
YAMETO	AMETO yield	0,1	g XAMETO. g SVFA-1
YHMETO	HMETO yield	0,1	g XHMETO. g SH2-1

Table A-18: General stoichiometry

Symbol	Name	Value	Unit
fE	Endogenous fraction (death-regeneration)	0,08	
iN,BIO	N content of biomasses	0,07	g N.g COD-1
iP,BIO	P content of biomasses	0,02	g P.g COD-1
iCV,BIO	Biomass XCOD/VSS ratio	1,42	g COD.g VSS-1
iCV,B	XB XCOD/VSS ratio	1,8	g COD.g VSS-1
iCV,U	XU XCOD/VSS ratio	1,3	g COD.g VSS-1
iCV,VFA	VFA SCOD/VS ratio	1,066	g COD.g VS-1
iCV,SB	SB SCOD/VS ratio	1,066	g COD.g VS-1
iCV,MEOL	MEOL SCOD/VS ratio	1,5	g COD.g VS-1
iCV,SU	SU SCOD/VS ratio	0,926	g COD.g VS-1
iCV,CB	CB SCCOD/VS ratio	1,8	g COD.g VS-1
iCV,CU	CU SCCOD/VS ratio	1,3	g COD.g VS-1
iCV,PHA	PHA XCOD/VSS ratio	1,67	g COD.g VSS-1
iCV,E	Xe XCOD/VSS ratio	1,42	g COD.g VSS-1
iCIT,BIO	Inorganic Carbon content of biomass	1,375	g TIC.g COD-1
iCIT,SB	Inorganic Carbon content of substrate and inert	1,05	g TIC.g COD-1
iCIT,MEOL	Inorganic Carbon content of methanol	0,917	g TIC.g COD-1

iCIT,CH4	Inorganic Carbon content of methane	0,6875	g TIC.g COD-1
iCIT,VFA	Inorganic Carbon content of VFA	1,375	g TIC.g COD-1
iCIT,CH	Inorganic Carbon content of Carbohydrates	1,375	g TIC.g COD-1
iCIT,PROT	Inorganic Carbon content of Proteins	1,32	g TIC.g COD-1
iCIT,LIP	Inorganic Carbon content of Lipids	0,968	g TIC.g COD-1
iCIT,PHA	Inorganic Carbon content of PHA	1,32	g TIC.g COD-1
iN,CB	N content of colloidal substrate	0,03	g N.g COD-1
iN,CU	N content of colloidal inert organics	0,01	g N.g COD-1
iN,SU	N content of soluble inerts	0,005	g N.g COD-1
iP,CB	P content of colloidal substrate	0,005	g P.g COD-1
iP,CU	P content of colloidal inert organics	0,005	g P.g COD-1
iP,SU	P content of soluble inerts	0,005	g P.g COD-1
YBOD,ult	Yield on ultimate BOD	0,95	
fBOD5,BODult	BOD5 to ultimate BOD ratio	0,65	
iIG	Synthesis inorganics in active biomass	0,11	g FSS.g COD-1
iN,XSTR	Nitrogen content of struvite	0,057075505	g N.g TSS-1
iP,XSTR	Phosphorus content of struvite	0,126214106	g P.g TSS-1
iP,XACP	Phosphorus content of ACP	0,162065388	g P.g TSS-1
iP,XVivi	Phosphorus content of Vivianite	0,123499858	g P.g TSS-1
iCa,PP	Calcium-PP molar ratio	0,08	mol Ca.mol P-1

iMg,PP	Magnesium-PP molar ratio	0,29	mol Mg.mol P-1
iK,PP	Potassium-PP molar ratio	0,26	mol K.mol P-1
iCAT,P	Cation content of SP,B	0	g Na.g P-1
fNa	Sodium mass fraction in NaCl	0,393372343	g Na.g NaCl-1

Table A-19: Diffusion coefficients - soluble compounds

Symbol	Name	Value	Unit
DSVFA	Diffusion coefficient of volatile fatty acids	0,000025	cm2.s-1
DSB	Diffusion coefficient of soluble degradable organics	0,0000124	cm2.s-1
DSMEOL	Diffusion coefficient of methanol	0,0000124	cm2.s-1
DSU	Diffusion coefficient of soluble undegradable organics	0,00001	cm2.s-1
DSNHx	Diffusion coefficient of total ammonia	0,00002	cm2.s-1
DSNOx	Diffusion coefficient of nitrate and nitrite	0,00001	cm2.s-1
DSN2	Diffusion coefficient of dissolved nitrogen	0,000019	cm2.s-1
DSN,B	Diffusion coefficient of soluble biodegradable organic N	0,0000124	cm2.s-1
DSPO4	Diffusion coefficient of orthophosphate	0,0000124	cm2.s-1
DSP,B	Diffusion coefficient of soluble biodegradable organic P	0,0000124	cm2.s-1
DSO2	Diffusion coefficient of dissolved oxygen	0,000025	cm2.s-1
DSCH4	Diffusion coefficient of dissolved methane	0,000025	cm2.s-1
DSH2	Diffusion coefficient of dissolved hydrogen	0,000025	cm2.s-1
DSCO2	Diffusion coefficient of dissolved carbon dioxide	0,00001	cm2.s-1
DSK	Diffusion coefficient of dissolved potassium	0,000019	cm2.s-1
DSCa	Diffusion coefficient of dissolved calcium	0,000019	cm2.s-1
DSMg	Diffusion coefficient of dissolved magnesium	0,000019	cm2.s-1
DSCAT	Diffusion coefficient of dissolved strong cations	0,000019	cm2.s-1
DSAN	Diffusion coefficient of dissolved strong anions	0,000019	cm2.s-1
DSH2S	Diffusion coefficient of hydrogen sulfide	0,000019	cm2.s-1
DSSO4	Diffusion coefficient of sulphate	0,000019	cm2.s-1
DSFe2	Diffusion coefficient of dissolved ferrous ion	0,000019	cm2.s-1