Cape Peninsula University of Technology

# TREATMENT OF POULTRY SLAUGHTERHOUSE WASTEWATER USING A PRETREATMENT STAGE, AN EXPANDED GRANULAR SLUDGE BED REACTOR COUPLED WITH A MEMBRANE BIOREACTOR

by

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# DECLARATION

I, **Honeil Basile Meyo**, declare that the content of this dissertation or thesis represents my own unaided work and that the thesis has not previously been submitted for academic examination towards any qualification. Furthermore, it represents my own opinions and not necessarily those of the Cape Peninsula University of Technology.

**30 June 2021**

**Signed** **Date**

# ABSTRACT

This study presents the biological treatment of poultry slaughterhouse wastewater (PSW) using a combination of a biological pre-treatment stage, an expanded granular sludge bed reactor (EGSB) and a membrane bioreactor (MBR) to treat PSW. This PSW treatment was geared towards reducing the concentration of contaminants present in the wastewater to meet the City of Cape Town (CoCT) discharge standards and evaluating an alternative means of treating medium to high strength wastewater at low cost. The EGSB used in this study was operated under mesophilic conditions and an organic loading rate (OLR) varying between 69 to 456 mgCOD/L.hr. The pre-treatment stage of this pilot plant played a big role in the processing of PSW, with removal percentages varying between 20 to 50% for the total suspended solids (TSS), 20 to 70% for the chemical oxygen demand (COD), and 50 to 83% for the fats oil & grease (FOG). The EGSB further reduced the concentration of these contaminants with removal percentages varying between 25 to 90% for the TSS, 20 to 80% for the COD, and 20 to >95% for the FOG. The last stage of this process, the MBR, contributed to a further decrease of the concentration of these contaminants with a peak performance of >95% for the TSS and COD removal percentages, and 80% for the FOG. Overall, the system (pretreatment-EGSB-MBR) exceeded the performance of 97% removal for the TSS and COD and a peak performance of 97.5% for the FOG removal. The results culminated in an effluent meeting the City of Cape Town municipal discharge standards.

**Keywords:** chemical oxygen demand (COD); expanded granular sludge bed reactor (EGSB); fats, oil, and grease (FOG); membrane bioreactor (MBR); poultry slaughterhouse wastewater (PSW); total suspended solids (TSS).

# DEDICATION

***To my parents:***

***My late mother, Meyo M'Obame Angelique nee Aboume***

***&***

***My father, Meyo M'Obame Basile***

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# RESEARCH OUTPUTS

The author of this thesis contributed to broaden the knowledge relevant to PSW treatment with the following publications:

**Publications:**

**The following international conference proceedings were published from previous studies related to this thesis:**

1. **Honeil B. Meyo**, Moses Basitere, Seteno K. O. Ntwampe and Cebisa T. Mdladla. Treatment of Poultry Slaughterhouse Wastewater using an Expanded Granular Sludge Bed Reactor Coupled with a Membrane Bioreactor and UV systems. Paper presented at the 16th South Africa International Conference on Agricultural, Chemical, Biological and Environmental Sciences (ACBES-19), 18-19 November 2019, Johannesburg, South Africa. Pp. 265. ISBN – 978-81-943403-0-0. Paper ID: EAP1119120. https://doi.org/10.17758/EARES8.EAP1119120
2. Cebisa T. Mdladla, **Honeil B. Meyo,** Moses Basitere and Seteno K. O. Ntwampe. Biological Pre-Treatment of Poultry Slaughterhouse Wastewater. Paper presented at the 16th South Africa International Conference on Agricultural, Chemical, Biological and Environmental Sciences (ACBES-19), 18-19 November 2019, Johannesburg, South Africa. Pp. 308. ISBN – 978-81-943403-0-0. Paper ID: EAP1119148. https://doi.org/10.17758/EARES8.EAP1119148.

**The following International conference presentation was delivered for research study related to this thesis:**

3. **Meyo H. B**., Basitere M., Ntwampe S. K. O., Mdladla C. T. Treatment of Poultry Slaughterhouse Wastewater Using an Expanded Granular Sludge Bed Reactor Coupled with a Membrane Bioreactor. Paper presented at 12th Eastern European Young Water Professionals Conference IWA YWP on Water Research and Innovations in Digital Era, 31 March -2 April 2021, Riga, Latvia. Pp 164. Book of Abstracts. http://iwa-ywp.eu/.

**The following DHET- accredited research article was published for research study related to this thesis:**

4. **Meyo, H.B.**, Njoya, M., Basitere, M., Karabo, S., Ntwampe, O. & Kaskote, E. 2021. Treatment of Poultry Slaughterhouse Wastewater (PSW) Using a Pretreatment Stage, an Expanded Granular Sludge Bed Reactor (EGSB), and a Membrane Bioreactor (MBR). Membranes, 11(5): 16. https://doi.org/10.3390/membranes11050345.

# LAYOUT OF THESIS

This thesis presents the biological treatment of PSW using a pre-treatment stage, anaerobic and membrane technologies such as the pre-treatment stage, an EGSB and the MBR. Therefore, the objectives of this thesis include the performance of biological combination consisting of a pre-treatment stage, an EGSB coupled with a MBR for the minimization of contaminants from PSW to meet municipal discharge standards. This thesis is composed of the following chapters:

- **Chapter 1**: Introduction. This chapter gives brief information on PSW with his characteristics, also elaborates a bit about water shortage and the motivation behind the design chosen to treat PSW. Furthermore, it provides a problem statement, hypothesis, research questions, aim and objectives, the significance and delineation of the study.

- **Chapter 2**: A literature review. This chapter elaborates on wastewater, the composition of PSW its characteristics and the process followed by the different treatment techniques of PSW, the MBR, the structure of membranes, AD and its driving parameters followed by the different types of anaerobic digesters, EGSB its characteristics and advantages and disadvantages of EGSB.

- **Chapter 3**: **Published as**: **Meyo, H.B.**, Njoya, M., Basitere, M., Karabo, S., Ntwampe, O. & Kaskote, E. 2021. Treatment of Poultry Slaughterhouse Wastewater (PSW) Using a Pretreatment Stage, an Expanded Granular Sludge Bed Reactor (EGSB), and a Membrane Bioreactor (MBR). Membranes, 11(5): 16. https://doi.org/10.3390/membranes11050345. This chapter describes the results, materials and methods used to treat the PSW, the sample collection for the pilot plant, the analytical methods to assess the quality of the feeds and products and also presents the results and discusses them.

- **Chapter 4**: Conclusions and recommendations. This chapter serves to conclude this thesis by listing key observations and lessons and provides recommendations to build upon for similar studies.

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# GLOSSARY

**Activated sludge** - Sludge that has experienced flocculation creating a bacterial culture commonly completed in tanks. Can be reached out with air circulation (Templeton & Butler, 2010).

**Alkalinity-** measures a substance aptitude to counteract acid (Grady *et* al., 2011).

**Anaerobic** – referring to a nonappearance of free oxygen (Rivière *et al.*, 2009).

**Biochemical oxygen demand (BOD)-**measures the concentration of organics within effluent (Gerardi, 2003).

**Chemical oxygen demands (COD)** - The quantity of chemical oxidant needed to decompose organic material (Gerardi, 2003).

**Digestion** - decomposition of sludge and additional waste biologically by microscopic organisms (Laiq Ur Rehman *et al.*, 2019).

**Dissolved oxygen (DO)**- the quantity of oxygen dissolved in water (Templeton & Butler, 2010).

**Expanded granular bed reactor (EGSB)** - Biological reactor which is different from the UASB reactor which utilised upward flow velocity through sludge bed (Gerardi, 2003).

**Hydraulic retention time (HRT)**- measures the normal time that a soluble compound stays in a biological reactor (Gerardi, 2003).

**Membrane** - a barrier that permits water to go through yet prevent undesirable substances from passing with it (Marchesi *et al.*, 2019).

**Membrane Bioreactor (MBR)** - the grouping of a membrane system with a biological reactor to isolate particles and substance compounds (Wiesmann *et al.*, 2007).

**Organic loading rate (OLR)** – The number of volatile solids being fed to the bioreactor every day (Grady *et al.*, 2011).

**Retention time**- the processing time of a given volume of wastewater in the reactor (Grady *et al.*, 2011).

**Total suspended solids(TSS)-** the total particles in solid which are in suspension in the wastewater (Tchobanoglous *et al.*, 2003).

**Total dissolved solids (TDS)-** the combination of all total dissolved solids (both organic and inorganic) inside wastewater (Tchobanoglous *et al.*, 2003)

# ABBREVIATIONS

| Abbreviation | Description |
|---|---|
| **AD** | Anaerobic digestion |
| **AGS** | Anaerobic granular sludge |
| **AOB** | Ammonium oxidizing bacteria |
| **BioERG** | Bioresource Engineering Research Group |
| **BOD** | Biological oxygen demand |
| **CoCT** | City of Cape Town |
| **CFM** | Crossflow membrane |
| **COD** | Total chemical oxygen demand |
| **CPUT** | Cape Peninsula University of Technology |
| **DAF** | Dissolved air flotation |
| **DWA** | Department of Water Affairs |
| **EC** | Electrocoagulation |
| **EGSB** | Expanded Granular Sludge Bed reactor |
| **FOG** | Fats, oil and grease |
| **HRAPs** | High rate anaerobic processes |
| **HRT** | Hydraulic retention time |
| **LRAPs** | Low rate anaerobic processes |
| **LSF** | Large scale fouling |
| **MBR** | Membrane bioreactor |
| **MF** | Microfiltration |
| **NF** | Nanofiltration |
| **NOB** | Nitrogen oxidising bacteria |
| **OLR** | Organic loading rate |
| **OWWTP** | Organic wastewater treatment plant |
| **pH** | Potential of hydrogen |
| **PSW** | Poultry slaughterhouse wastewater |
| **PT** | Primary treatment |
| **RO** | Reverse osmosis |
| **SA** | South Africa |
| **SANS** | South African National Standards |
| **SMBR** | Submerged membrane bioreactor |
| **SND** | Simultaneous nitrification and denitrification |

| | |
|---|---|
| **SRT** | Sludge retention time |
| **SS** | Suspended solids |
| **SSF** | Smaller-scale fouling |
| **ST** | Secondary treatment |
| **tCOD** | Total chemical oxygen demand |
| **TDS** | Total dissolved solids |
| **TN** | Total nitrogen |
| **TP** | Total phosphorous |
| **TSS** | Total suspended solids |
| **UF** | Ultrafiltration |
| **VA** | Volatile acid |
| **VFA** | Volatile fatty acids |
| **VS** | Volatile solid |
| **VSS** | Volatile suspended solids |
| **WWT** | Wastewater treatment |

# LIST OF SYMBOLS

| Symbol | Description | Units |
|---|---|---|
| **°C** | Degrees Celsius | |
| **Vw** | Working Volume | $m^3$ |
| **Q** | Flow rate | $m^3$/day |
| **HRT** | Hydraulic retention time | days or hours |
| **OLR** | Organic loading rate | kg COD/$m^3$·d or g tCOD/L.day |
| **COD** | Chemical oxygen demand | kg COD/$m^3$ |
| **Vup** | upflow velocity | m/h |
| | Concentration | mg/L |
| ***J*** | permeate flux | L/$m^2$h |
| **A** | Surface area | $m^2$ |

| Chemicals Formula | names |
|---|---|
| $CH_4$ | Methane |
| $CO_2$ | Carbon dioxide |
| $CO^{2-}$ | Carbonate |
| $H_2$ | Hydrogen |
| $H_2O$ | Water |
| $H_2S$ | Hydrogen sulphide |
| $HCO_{3-}$ | Bicarbonate |
| $H_2CO_3$ | carbonic acid |
| $NH_3$ | Ammonia |
| $NH_4$-N | Ammonium nitrogen |
| $NH_4^+$-N2 | Ammonium nitrogen |
| $NO_3$-$N_2$ | Nitrate nitrogen |
| $NO_2$-N | Nitrite nitrogen |
| $NO_2$ | Nitrite |
| $NO_3$ | Nitrate |
| $O_2$ | Dioxygen |
| $PO_4^{3-}$ | Phosphate |
| $SO_4^{2-}$ | Sulphate |

# CHAPTER 1

# INTRODUCTION

# Chapter 1: Introduction

## 1.1. Background of the study

South Africa (SA), precisely Cape Town, experienced a water crisis combined with a high demand of potable water from poultry product producers and urban areas. The lack of water is attributed to environmental changes among other issues, which makes it an urgent priority for the Cape Town metropole, to create water preservation techniques to limit potable water consumption by the poultry industry (Njoya *et al.*, 2019). The improvement of creative effluent treatment processes is thusly principal in endeavouring to reduce the enormous amount of wastewater produced, and to deal with the ecological wellbeing concerns emerging from poutry slaughterhouse wastewater (PSW) discharge into the environment (Bustillo-Lecompte & Mehrvar, 2017). Besides, expanding effluent treatment costs and the execution of progressively severe government enactments to alleviate ecological contamination while limiting new water source pollution, necessitates that PSW is satisfactorily treated before discharge (Del Nery *et al.*, 2001; Avula *et al.*, 2009).

This research explored the possibility to treat PSW to a water quality standard which complies with City of Cape Town (CoCT) industrial wastewater discharge standards and also for reuse purposes. Some past studies have investigated the treatment of PSW using biological systems. One of these past studies met challenges when using an EGSB combined with an anoxic-aerobic tanks, for which the system experienced sludge washout during high fats, oil & grease (FOG) and high suspended solids loading (Basitere *et al.*, 2016; Meyo *et al.*, 2021). Also, a comparable study was done by Sheldon & Erdogan (2016) who reported that a combined EGSB/MBR for treating soft drink industry wastewater encountered challenges when removing all macronutrients when the EGSB was used as a primary treatment unit (Meyo *et al.*, 2021). However, Sheldon & Erdogan (2016) further reported tCOD removal of 95% by using a joint EGSB/MBR for treating soft drink industry wastewater.This motivated the design of this research study, which focused on treating PSW using a pre-treatment stage, an Expanded Granular Sludge Bed Reactor (EGSB) coupled with a Membrane Bioreactor (MBR).

Due to the absence of promoting cutting-edge affordable effluent treatment option in the Cape Town metropole, it is a crucial necessity to develop effective and cheap solutions for medium- to high-strength wastewater treatment. This study aims at investigating the effectiveness and performance of using a combined pre-treatment stage, an EGSB coupled with a MBR, for use by poultry slaughterhouses.

## 1.2. Problem statement from the research study

SA is facing an alarming water crisis due to the high demand of potable water by urban areas and also from one of the biggest industries in the agricultural sector which is the poultry industry (Basitere *et al.*, 2016; City of Cape Town, 2018). To carry on different tasks, poultry slaughterhouses use a significant quantity of potable water to process birds. This high production of poultry products is geared towards satisfying the growing demand for affordable white meat (Njoya *et al.*, 2019). This high consumption of potable water culminates in the high generation of PSW containing organic matter, suspended solids, nitrogen, phosphorus and pathogens (Bustillo-Lecompte & Mehrvar, 2017). Due to the occurrence of these pollutants, the effluent does not meet the City of Cape Town industrial discharge standards. This implies it can pollute other local water sources whenever discharged unprocessed. Therefore, an appropriate configuration for treating PSW needs to be designed and assessed for usage, especially in Cape Town.

## 1.3. Hypothesis

A pre-treatment stage, an EGSB combined with an MBR can treat PSW to meet City of Cape Town (CoCT) industrial discharge standards.

## 1.4. Research questions

- What is the performance of the pre-treatment stage with respect to pollutant removal?
- What is the performance of the EGSB in terms of pollutant removal?
- What is the performance of the MBR in terms of pollutant removal?
- What is the overall system (pre-treatment-EGSB-MBR) performance in terms of pollutant removal?
- Are more post-treatment options required to reach municipal wastewater discharge standards using the biological arrangement suggested by this study?

## 1.5. Research aim and objectives

This research aims to assess the performance of a treatment system consisting of a pretreatment stage, an EGSB joined to a MBR for pollutant removal from PSW to meet CoCT discharge standards.

For this aim to be achieved, the following objectives were developed:

- Determine the performance of the pre-treatment stage with respect to pollutant removal.
- Determine the performance of the EGSB in terms of pollutant removal.
- Determine the performance of the MBR in terms of pollutant removal.

- Determine the overall system (pre-treatment-EGSB-MBR) performance in terms of pollutant removal.
- Determine if the final effluent from the MBR unit meet the CoCT industrial discharge standards.

## 1.6. Significance of this research

The treatment of the PSW has been done using multiple technologies. Aerobic treatment is mostly costly; therefore, the use of an anaerobic digester is better in terms of cost, organic matter removal, minimization of sludge produced and biogas production. Water scarcity is currently an issue in South Africa, and the problem is set to continue due to issues such as climate change and a growing population that is increasing the water demand in urban areas. Designing a new PSW configuration to treat wastewater, in particular PSW, and produce bio-methane, which is an alternative source of energy, can enhance the ecological wellbeing of the environment which poultry slaughterhouses operate. Such systems will allow industries to recycle their wastewater and use less potable water; therefore, reducing the pressure on the country's water supply.

## 1.7. Delineation of the research

This study will not concentrate on:

- Economics aspects of the PSW treatment pilot plant.
- Production of biogas.
- The procedures associated with the treatment of biogas for commercialisation.
- UF submerged membrane fouling effects, process modelling and kinetics.
- The kinetics growth of organisms in each treatment unit in the PSW pilot plant.
- Total nitrogen (TN) removal using a simultaneous nitrification-denitrification.

# CHAPTER 2

# LITERATURE REVIEW

**Part of this literature review has been published in a conference proceeding as**:

**Honeil B. Meyo**, Moses Basitere, Seteno K. O. Ntwampe and Cebisa T. Mdladla. Treatment of Poultry Slaughterhouse Wastewater using an Expanded Granular Sludge Bed Reactor Coupled with a Membrane Bioreactor and UV systems. Paper presented at the 16th South Africa International Conference on Agricultural, Chemical, Biological and Environmental Sciences (ACBES-19), 18-19 November 2019, Johannesburg, South Africa. Pp. 265. ISBN – 978-81-943403-0-0.Paper ID: EAP1119120. https://doi.org/10.17758/EARES8.EAP1119120.

# Chapter 2: Literature review

## 2.1. Wastewater

The term wastewater translates to “utilized water”, and is generated from the industrial processes (textile, domestic, municipal, industrial, agricultural, etc.) that utilize moderate or extensive potable water (Pescod, 1992; Rabah, 2010). Wastewater can be qualified as untreated when its concentration of contaminants hasn’t been reduced to discharge standards (South African water act, 1998). The major contaminants of poultry slaughterhouse wastewater are organic matter, and FOG. These should be removed before the wastewater is discharged into the environment prevent the pollution of the environment because the wastewater consists of organic matter with a high chemical oxygen demand (COD), total suspended solids (TSS) or Biological oxygen demand ($BOD_5$), FOG, etc. Depending on the concentration of contaminants in the wastewater, the rotten egg smell, stem from $H_2S$ production that result from the biodegradation of contaminants in the wastewater (Rabah, 2010). The odour is as a result of decomposition of several pollutants including carcass debris by microorganisms and it is associated with the release of some gases, such as $H_2S$, which promote odour. These microorganisms prevail under mild to moderate temperatures and are inactive under high and low temperatures (>4 ˚C). When the wastewater is of high strength, microbial development multiplication is predominant. Further components such as nutrients (nitrogen and phosphorous mixes) and inorganic matter, play a big role in eutrophication, a phenomenon that seriously affects water bodies due to the oversupply of nutrients and organic matter (Lapointe *et al.*, 2015). Various industries generate high strength industrial wastewater, subsequently, its features vary from one industry to another.

## 2.2. Wastewater treatment plants

Wastewater treatment plants aim to address ecological pollution by using advance treatment options to remove contaminants from various streams of wastewater. To avoid financial penalties associated with levies from the discharge of untreated wastewater, industries are required to treat their wastewater before discharge. This incentive is geared towards protecting the aquatic fauna and the flora surrounding waterbodies (Njoya *et al.*, 2019). Wastewater contributes immensely to ecological contamination challenges; it imperils human and amphibian life including other animals on the off chance that it is released untreated into clean water streams (Chávez *et al.*, 2005; Lo *et al.,* 2005; Yetilmezsoy & Sakar, 2008; Plumber *et al.*, 2012). Most wastewater is composed of pollutants quantifiable by wastewater assessment parameters such as TSS, COD, $BOD_5$; nutrients; FOG; and traces of inorganic contituents (Lo *et al.,* 2005; Chávez *et al.*, 2005; Plumber *et al.*, 2012).

Similarly, microorganisms are found in wastewater and can be pathogenic or not. Microscopic organisms that endure the cleaning anti-microbial products utilized, also end inside the wastewater (De Nardi *et al.*, 2011). The average concentration of $BOD_5$ and COD in slaughterhouses are extensively higher than those from household anthropogenic activity (Rajakumar *et al.*, 2012).

### 2.3. Poultry slaughterhouse wastewater (PSW)

Potable water is extensively used in poultry processing plants. Generally, 38 litres of potable water is required for the processing of a broiler. The water demand for the processing of birds relates to their size. This is illustrated by the processing of turkeys which requires more water for a single bird than chickens (Hydro-Flo Technologies, 1990). From these processing operations, the wastewater generated will be laden with feathers, faeces, blood, nutrients and carcass debris. The waste load can be determined by water quality assessment parameters, including BOD, TSS concentration, COD, FOG, yet most poultry processing plants, frequently assessed for $BOD_5$, which is a measure of the required concentration of $O_2$ required for the reduction of most pollutants in the wastewater in 5 days (Jayathilakan *et al.*, 2012).

### 2.4. The characteristics of poultry slaughterhouse wastewater

The main pollutants in PSW stems from the excrement, pee, blood, built-up fats, carcass, and non-processed feed in the digestive organs of the butchered birds and the cleaning of the slaughterhouse facilities. The composition of the abattoir wastewater differs as per the water and industrial process used (Bustillo-Lecompte *et al.,* 2016). The PSW generated from the poultry industry globally represents an environmental concern because of the slaughterhouse wastewater content of proteins, filaments, FOG, high strength organic matter content, and pathogens (Bustillo-Lecompte et al., 2016; Bustillo-Lecompte & Mehrvar, 2017). Distinctive features of an untreated PSW in Cape Town are listed in Table 2.1 and Table 2.2. These Tables provide the characteristics of raw PSW in Cape Town in contrast to the consumable water limits and industrial wastewater release.

**Table 2. 1:** Distinctive features of an untreated poultry slaughterhouse wastewater(non-filtered) in Cape Town (Basitere *et al.,* 2019)**.**

| Parameter | Unit | PSW | |
|---|---|---|---|
| | | Range | Average |
| pH | - | 6.1-7.2 | - |
| TDS | Ppm | 691-1,693 | 1,138 |
| Conductivity | µS/cm | 973-2,403 | 1,604 |
| Turbidity | NTU | 237-997 | 719 |
| Salinity | Ppm | 529-1,413 | 916 |
| TSS | mg/L | 313-8,200 | 1,654 |
| VSS | mg/L | 239-8,920 | 1,906 |
| COD | mg/L | 2,517-12,490 | 5,216 |
| $NH_4^+$-N | mg/L | 135-447 | 216 |
| $NO_3^-$N | mg/L | 0.63-22.7 | 3,33 |
| $PO_4^{3-}$P | mg/L | 29-54 | 38 |
| VFA | mg/L | 105-898 | 375 |
| Alkalinity | mg/L | 322-923 | 499 |
| FOG | mg/L | 156-1,710 | 715 |
| $BOD_5$ | mg/L | 925-5,000 | 2,477 |

## 2.5. Guidelines for slaughterhouse wastewater management

Guidelines are important to mitigate the ecological effect of the discharge of untreated PSW and provides a target for a designed wastewater treatment process. The consistency with present legislation and the state-of-the-art advancements may likewise give some financial relief through resource recovery such as biogas production utilizing high-rate anaerobic treatments (Bustillo-Lecompte & Mehrvar, 2017). Table 2 describes present guidelines and discharge limits for pollutants in wastewater for an adequate discharge standard to the environment.

**Table 2. 2:** Department of water affairs (DWA,2010), South African National Standards(SANS 241;2015) drinking water standard(2015)and City of Cape Town discharge standards(Rinquest *et al.*, 2019).

| Parameter | Units | PSW | | |
|---|---|---|---|---|
| | | aDWA (2010) by law limit | bCoCT by-law limits | cSANS 241;2015 |
| Potential Hydrogen (pH) at 25°C | | 5.50 to 9.50 | 5.5 -9.5 | 5.50 to 9.50 |
| Conductivity | mS/m | 70 to 150 | 500 | <150 |
| Chemical oxygen demand (COD) | mg/L | 5000 | 5000 | 1000-2400 |
| Suspended Solids (SS) | mg/L | nd | 1000 | nd |
| Total dissolved solids (TDS) at 105°C | mg/L | nd | 4000 | <1000 |
| Total Sulphates (SO42-) | mg/L | nd | 1500 | <400 |
| Oil and grease (O&G) | mg/L | 2.5 | 400 | nd |
| Total Phosphorous | mg/L | 5 | 25 | nd |
| Faecal Coliforms per 100mL | | 1000 | nd | nd |
| Turbidity | NTU | nd | nd | <1 |
| Ammonia as being Nitrogen (N) | mg/L | 6 | 6 | <1 |
| Dissolved organic carbon (DOC) | mg/L | nd | nd | <10 |
| Nitrates | mg/L | 15 | 10 | nd |
| Temperature (at 25) | °C | nd | 0 ≤ 40 | nd |

[a]DWA: department of Water Affairs (2010), [b]CoCT by law limit: City of Cape Town wastewater and industrial waste (2013), [c]SANS 241;2015: South African National Standards 241; drinking water standards (2015), nd: not designated.

## 2.6. Ecological effects of the discharge of untreated PSW to the environment

The increasing demand for poultry products, increases the use of potable water usage to accommodate the increased throughput of poultry slaughterhouse facilities. This culminates in the increase in the production of PSW. Despite the ability of the environment to naturally process moderate concentration of contaminants in wastewater, the high concentration of these contaminants in the PSW, imposes a greater contamination threat particularly when released into the environment without treatment (Bustillo-Lecompte & Mehrvar, 2017).

The release of untreated PSW to water sources, influences the quality characteristics of the receiving water bodies by causing a decrease of dissolved oxygen, which may endanger aquatic life. Additionally, nitrogen and phosphorus constituents in the wastewater may cause eutrophication (Olowoporoku, 2016). The release of these nutrients, oversupplies nutrients to aquatic plants, in particular invasive species, which grow exponentially. In this way, the further growth of algal blooms cause by wastewater contamination, may prompt the degenerate sea-going life because of the depletion of dissolved oxygen levels. At last, slaughterhouse wastewater may contain heavy metals such as chromium and unionized alkali compounds, which are very poisonous to aquatic life and humans (Bustillo-Lecompte *et al.,* 2016).

Another source of pollution from the slaughterhouse industry is the increase of surfactants usage that are contained in the cleaning products used in poultry slaughterhouses. Surfactants, which are high concentration in detergents, may enter the sea-going water sources, due to the insufficient slaughterhouse wastewater treatment, causing short-term and long-term changes in the environment (Bustillo-Lecompte *et al.*, 2016; Bustillo-Lecompte & Mehrvar, 2017).

The ecological effect of PSW isn't just because of surfactants, nitrates, and chloric anions, but also contains pathogens, which endure the bird processing and facility cleaning operations, and can thus proliferate continuously. Pathogens from slaughterhouse wastewater can likewise be transmitted to people exposed to the untreated PSW. In this manner, PSW must be treated adequately before releasing it into water sources to maintain reduced ecological contamination and the endangerment of life in the receiving waters (Bustillo-Lecompte *et al*., 2016; Bustillo-Lecompte & Mehrvar, 2017).

## 2.7. Treatment techniques of poultry slaughterhouse wastewater

### 2.7.1. Pre-treatment techniques of poultry slaughterhouse wastewater

The main purpose behind the primary treatment of PSW is to minimise the concentration of solids and coarse solids from the PSW and this minimisation can contribute to the reduction of FOG as well as $BOD_5$ as organic matter is entrapped by solids including feathers, blood flocs, meat trimmings and FOG (Bustillo-Lecompte & Mehrvar, 2017). The most popular pre-treatment techniques used consists of screens, settling tanks and flotation equalization tanks for removal of solids in the wastewater. Screens were used in this study and as discussed in subsequent sections. In this manner, huge solids with a radius/diameter of 10 to 30 millimetre (mm) are removed from the PSW (Mittal, 2006). A new organic fluid called Ecoflush was used in the pre-treatment tank after the screening of the PSW, prior to anaerobic treatment study and is also discussed in subsequent sections.

#### 2.7.1.1. Screeners

The screening procedure is the initial phase in wastewater treatment and it expels a vast quantity of suspended solids (SS) and thick particulate matter such as fat, bone, hair and meat trimmings lost during the butchering procedures (Templeton & Butler, 2010; Mittal, 2006).

#### 2.7.1.2. Ecoflush

Ecoflush is an assembly of microscopic organisms with hydrolysis potential that are isolated from the soil and put into a bottle in a sleeping state and are triggered when the wastewater is applied. Its constituted by glaucids and amino acids which form ground-breaking disintegrating agents that invigorate the natural tendency of specific microorganisms to deliver enzymes (hydrolases) equipped for separating the hydrocarbons in organic matter (Ergofito, 2019). Ecoflush also oxidises $NH_3$ into $NO_3^-$ and $NO_2^-$ and also eliminates $NH_3$. The terrible odours are removed at their origin by the useful microorganisms utilized in Ecoflush, and it rapidly diminishes the population of pathogenic microbes that cause the awful odour, by oxidising the rotting organic substances into stable ones (Ergofito, 2019). Furthermore, Ecoflush separates the hydrocarbon chains in FOG and it promotes $NH_3$ and $H_2S$ decomposition, therefore reducing the odorous potential of high strength wastewater (Ergofito, 2019).

The Ecoflush was used because of the following advantages (Ergofito, 2019):

- The Lowering of COD and BOD levels in wastewater
- Low-tech application and easy to use
- Removes bad smells immediately
- Removes FOG’s from grease traps
- Guarantee municipal compliance with effluent water discharge standards.

### 2.7.2. Physical and chemical treatment

After the preliminary treatment or pre-treatment, the wastewater ought to be subsequently treated utilizing primary treatment (PT) and secondary treatment (ST) systems. One of the most viable techniques for the PT of PSW is dissolved air flotation (DAF) to induce the decrease of FOG, TSS and $BOD_5$ (Bustillo-Lecompte & Mehrvar, 2017). The most utilized physical and chemical treatment strategies are discussed in the following subsections.

#### 2.7.2.1. Dissolved air flotation (DAF)

The DAF method is a prominent technique of PT. DAF is a typical technique to decrease the concentration in suspended solids (SS), $BOD_5$ and FOG of PSW. Be that as it may, different techniques can achieve the comparable outcomes requiring little to no effort. In DAF, air infused at the base of the flotation container, transport light solids and other material, for example, fat and grease (F&G), to the surface of the wastewater whereby the pollutants are reliably skimmed off. DAF can isolate light or little particles to an appreciable extent and in a short time than gravity settling (Dlangamandla, 2016). In this technique, the whole or a small quantity of the WW is supplied with air at 250 to 300 kilopascal (kPa) which is brought into a flotation container. Some polymers and flocculants are frequently blended with the wastewater before the DAF process for better pollutant removal. Blood coagulants, as well as flocculants, are added to the wastewater to expand protein floc formation and grease flotation. The addition of flocculants into DAF units can accomplish the reduction of COD in the range 32% to 90% and are fit for clearing a lot of nutrients (Heninger, 2017; Mittal, 2006; Templeton & Butler, 2010). However, basic DAFs have some drawbacks, resulting in moderate nutrient removal (Bustillo-Lecompte & Mehrvar, 2017).

#### 2.7.2.2. Sedimentation and coagulation-flocculation procedure

PSW has waste which can stay in suspension, or yet, settle due to gravity. The sedimentation technique is utilized for the removal of solids from the wastewater and reduces the concentration of solids. Sedimentation is utilized in both the PT and ST phases of wastewater treatment (Templeton & Butler, 2010). In abattoir wastewater (AWW), colloidal particles are gathered into bigger particles known as flocs. In AWW, the colloidal particles have negatively charged ions which make them steady and reluctant to accumulation. Therefore, coagulants with positively charged properties are added to undermine the colloidal particles repulsion, to form flocs and to encourage sedimentation. Different coagulant types can be found and the most broadly utilized are inorganic metal based-coagulants with elimination efficiencies of up to 80% for BOD, COD, and TSS (Bustillo-Lecompte & Mehrvar, 2017). Coagulation–flocculation procedures have been done for the treatment of AWW (Mittal, 2006).

#### 2.7.2.3. Electrocoagulation (EC)

The EC is an innovative treatment method that makes use of electrical flow to treat and flocculate pollutants without including coagulants. Likewise, EC could lessen the pollutants in wastewater. It consists of sets of metal sheets called conductors, that are arranged as anodes and cathodes. The cathode loses electrons, while the water is gaining electrons. In this manner, oxidation-reduction reactions ensue, resulting in wastewater pollutant decomposition

(Liu et al., 2010). The EC method has been utilized as a low-cost innovation for the minimisation of organic matter, and pathogens from slaughterhouse wastes (SW) by actuating an electric flow without the accumulation of chemicals in the final treated water. It can rejuce up to 50% to 98% for $BOD_5$, 95-99% for TSS and 95-99.99% for microorganisms (Tetreault, 2000).

### 2.8. Membrane processes: advantages and drawbacks

An alternative treatment technique for birds processing wastewater, is the membrane processes (Onsekizoglu, 2012). There are various kinds of membrane systems with the most popular being microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO) which have been utilized for abattoir wastewater treatment to minimise the concentration of particulates, colloids, macromolecules, carbon-based matter, and pathogens with significant efficiencies of up to 90%. Be that as it may, membrane treatment processes are required to be combined with conventional procedures for nutrient removal in abattoir wastewater (Bustillo-Lecompte & Mehrvar, 2017).

The membrane units/processes are known to have some advantages which include (Heidlberger & Neugebauer, 2015):

- Eco-friendly
- Simply combined with different procedures and operations
- Produces treated water with high-quality
- No synthetic compounds (chemicals) needed

Even though these benefits give rise to membrane units use in wastewater treatment, there are a few drawbacks related to their utilization namely (Heidlberger & Neugebauer, 2015):

- The necessity to exchange membranes regularly because of the fouling of the membrane

### 2.9. Membrane bioreactor (MBR) systems

MBR consists of the grouping of membrane filtration and a wastewater treatment tank within the same unit. They have shown good performance for the removal of carbon-based (organic) and non-carbon based (inorganic) pollutants from wastewater (Iorhemen *et al.,* 2016). Points of interest of the membrane bioreactor is that it incorporates biological treatment, superb final treated water quality free of microscopic organisms and pathogens, has a small plant footprint, and can handle elevated organic matter loading rates. Overall, further technological advancements occurred in the late 1980s, with the MBR process being implemented as an alternative to the conventional activated sludge processes (Abdel Kader, 2015).

### 2.9.1. System arrangements

MBR consist of two essential parts, the organic matter treatment unit in charge of the biodegradation of the effluent and the membrane module for the physical separation of the treated water. The dynamic force over the membrane is accomplished by pressurizing the bioreactor or making negative pressure on the permeate side (Abdel Kader, 2015). Cleaning of the membrane is accomplished through a regular back flush and infrequent chemical backwashing. A diffuser is typically set-up underneath the membrane module to encourage scouring of the filtration surface. Air circulation and blending are likewise accomplished by the unit. The anoxic section or anaerobic section can be merged to allow concurrent organic nutrient removal (Templeton & Butler, 2010). The fouling of membranes or is brought about by build-up of feed water constituents on the outside of the membrane (cake as well as gel development) or in the membrane matrix (pore blocking as well as adsorption). The nature and degree of the fouling are influenced by the membrane properties, conditions of operation (like air circulation), and wastewater properties (van der Marel *et al.*, 2010).

The second section includes the distribution of the blended wastewater through a partition. The determined power is the pressure made by the high cross-stream velocity along the partition surface (You *et al.*, 2006).

Various membrane designs have been utilized for MBR applications. These incorporate cylindrical, plate and casing, rotational circle, empty fibre, carbon-based, metallic, and non-carbon-based microfiltration and ultrafiltration membranes. The pore size of layers utilized is 0.01 to 0.4 micrometre (µm). The trans-membrane pressure ranges from 20 to 500 kPa for internally skinned membranes and up to 10 to 80 kPa for externally skinned membranes (Abdel Kader, 2015).

### 2.9.2. Structure of membranes

The efficiency of membranes is portrayed by the permeate flux and retention. The structure or configuration of membranes assumes a significant role in the mechanism of transport. In the treatment of wastewater, the kind of membranes utilized is dictated by the size of pollutants. The particles that are suspended, with a molecule size of 100 and 1000 nm are normally isolated utilizing MF. Pollutants such as microscopic organisms, macromolecules and low sub-atomic weight proteins with a molecule size of 5 and 100 nm, are generally isolated utilizing UF. NF and RO can remove species with a molecule size less than 5 nm, which permits the removal of salts and low atomic weight sugars. MF and UF are usually used in membrane separation process utilized in WWTPs due to fouling minimization and reduction of costs (Marchesi *et al.*, 2019). Among those membranes, a UF membrane was used for this study.

#### 2.9.2.1. PSW treatment using UF membrane process

The UF membrane eases the removal of colloidal material, SS and macromolecular materials including proteins based on the structure, physical form and molecular weight of these pollutants. Therefore, UF as a semi-porous membrane can be useful in this regard (Gupta *et al.*, 2008). UF MBR's can work at 1 MP for pressure to remove particulate material with a size of 5 to 100 nm (Marchesi *et al.*, 2019). In PSW, UF membranes had confirmed to be effective in the removal of pathogens, particulate material and nutrients; and also proved its appropriateness as a secondary or tertiary treatment process for the anaerobic treatment of PSW (Basitere *et al.*, 2017).

According to Yordanov (2010), the UF membrane efficiency in terms of FOG and TSS removals was 99% and 98%, respectively, and the removal of $BOD_5$ and COD was above 94% in a study done to assess the efficiency of UF treatment of PSW. Basitere *et al.*, (2017) reported that COD removal was 64%, TSS removal was 88% and FOG removal was 48% with the use of UF membrane as a post-treatment process in a study conducted on treating PSW using SGBR coupled with an UF membrane system. Moreover, Williams (2017) reported a better performance was observed for the UFMBR with an EGSB product achieve removal efficiencies of 97%, <50%, and 62% for turbidity, TSS and tCOD when compared to MF membrane system.

#### 2.9.2.2. Membrane permeation flux

The permeation flux is characterized as being the volume moving through the membrane per unit area per unit time. The higher permeation flux brings about the development of fouling on the membrane surface, which represents a challenge, albeit, a higher operational permeation flux is attractive for economical operation of the unit. It is important to operate below the limit flux to control the rate and level of fouling (Marchesi *et al.*, 2019). The flux can be calculated using Eq. 2.1 (Marchesi *et al.*, 2019):

$$J = \frac{Q}{A_{membrane}} \qquad 2.1$$

Where: Flux ($J$) is in $L.m^{-2}h^{-1}$; permeate flow rate (Q) is determined in L/h, and the membrane permeation area ($A_{membrane}$) is determined in $m^2$.

#### 2.9.2.4. Factors affecting flux in UF systems

UF membrane can be utilisedfor PSW treatment as a secondary or tertiary treatment system. The principal parameter of operation in UF is simply, the maintenance of the permeation flux and reduction of its vulnerability to pore structure fouling. During UF unit operation, permeate flux is steadily reduced and membrane fouling becomes obvious when all other parameters of operation (pH, transmembrane pressure (TMP), the flow rate of feed) stays consistent. Since protein particles don't have a fixed physical conformation, it is expected to encounter an underlying lessening in permeate flux when utilizing UF membranes for protein-laden wastewater, such as PSW (Marchesi *et al.*, 2019).

**2.10. Anaerobic digestion (AD)**

It has been shown in the study done by Appels *et al.* (2008) that anaerobic digestion (AD) enhances the wastewater treatment in WWTP and is thus considered to be a vital part of a WWTP. Salihu & Alam (2016) highlighted that AD is a reaction system which decomposes organic matter under anaerobic conditions. The research being reported concurred that AD utilises micro-organisms under oxygen-free conditions (Sawyerr *et al.*, 2019). According to Salihu & Alam (2016), the end product of the AD process includes:

- 60 – 70 % biogas ($CH_4$)
- 30 – 40 % $CO_2$

Where the rest are impurities.

Salihu & Alam (2016) highlighted that pre-treatment of the wastewater is a required step to accelerate anaerobic digestion as well as to be able to obtain suitable treated water. Appels *et al.* (2008) stated that even though there are different routes for managing municipal water, AD can further transform organic matter into biogas.

AD is utilized in the treatment of agricultural wastes, food wastes and wastewater. Salihu & Alam (2016) noted that AD is capable of reducing chemical oxygen demand (COD) and biological oxygen demand (BOD) from waste streams. AD is a complex process that depends on many conditions among which the coordination of the activity of the microbial communities is required. As illustrated in Figure 2.1, anaerobic digestion consists of four stages that occur simultaneously: hydrolysis, acidogenesis, acetogenesis, and methanogenesis (Appels *et* al. 2008).

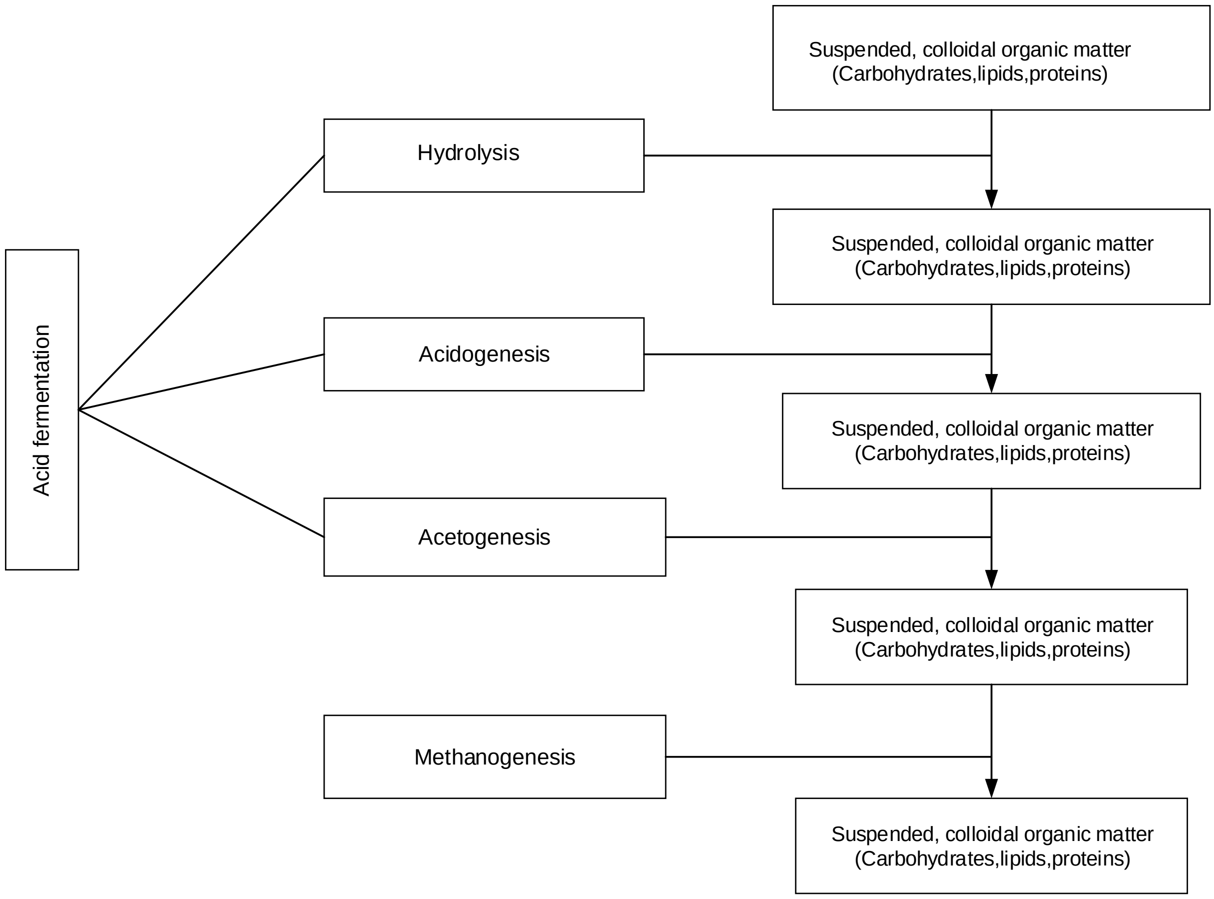


**Figure 2. 1: Anaerobic digestion stages** (Grady *et al.*, 2011)

### 2.10.1. Principles of anaerobic digestion

#### 2.10.1.1. Enzymatic hydrolysis

During this step, macromolecules such as lipids, polysaccharides, proteins and nucleic acids are disintegrated into soluble species (mostly sugars, amino acids and fatty acids). The hydrolysis or solubilisation process is affected by the action of exo-enzymes excreted by fermentation bacteria. Overall, hydrolysis is a process that takes time and may limit the anaerobic digestion process. Thus, it is considered to be the rate-limiting step. Many pre-treatment processes can be used to increase the hydrolysis rate by increasing the biodegradability of the organic matter in the wastewater (Appels *et* al. 2008).

#### 2.10.1.2. Acidogenesis

Acidogenesis or acidification is the stage where the hydrolysed products are converted into simple molecules with low molecular weight, like volatile fatty acids (e.g. acetic-, propionic and butyric acid), alcohols, aldehydes and gases like $CO_2$, $H_2$ and $NH_3$. Acidogenesis occurs under the action of a variety of bacteria, mostly anaerobic, meaning that they operate in the absence of oxidants like oxygen or nitrate. Luckily for these anaerobic bacteria, there will always be oxygen-consuming bacteria within the system so that the oxygen is removed whenever it is available. These oxygen-consuming bacteria are required to remove all the oxygen present in the AD system (Appels *et* al. 2008).

#### 2.10.1.3. Acetogenesis

In this stage, the products from acidification are subject to the action of acetogenic bacteria which convert them into acetic acid, hydrogen and carbon dioxide. The first three steps of anaerobic digestion are grouped into what is referred to as acid fermentation. During acid fermentation, no organic matter leaves the liquid phase but it is merely converted into a suitable form for the final step, that is, methanogenesis (Appels *et* al. 2008).

#### 2.10.1.4. Methanogenesis

Methanogenesis is the last step of the AD process where acetic acid and hydrogen are converted into $CO_2$ and $CH_4$ under the action of methanogenic bacteria. It is the only stage which allows most of the organic matter to leave the liquid phase, in the form of produced methane gas leaves the liquid phase and is transformed into the gas phase (Appels *et* al. 2008).

### 2.10.2. Driving parameters of AD

Anaerobic digestion depends upon several parameters among which the most predominant are (Laiq Ur Rehman *et al.*, 2019):

- Temperature
- pH
- Alkalinity and pH
- VFA/alkalinity ratio
- Carbon: Nitrogen ratio
- Organic loading rate (OLR)
- Retention times (HRT & SRT)

These parameters have a direct impact on the microbial communities, rate of biological reactions, biogas production and overall efficiency of the process (Laiq Ur Rehman *et al.,* 2019).

#### 2.10.2.1. Temperature

One of the most important parameters that impact the AD process is temperature because different methanogens are sensitive to a variation in temperature. Indeed, even a couple of degrees' discrepancy in operating temperature of AD, can modify not only biological activity but also methane production. AD has been done at various temperature ranges, however, an ideal temperature is important for steady and effective fermentation. Generally speaking, there are three popular ranges of AD that are psychrophilic AD which ranges between 10 to 20 °C, mesophilic AD from 30 to 40 °C, and thermophilic AD between 50 to 60 °C. Biogas production is more prone to happen during mesophilic and thermophilic AD and the choice of each process relies upon various factors (Wiesmann *et al.*, 2007). Due to elevated temperature, thermophilic AD has many benefits such as elevated metabolic rates, excessive biogas yields and the pathogens are deactivated. In any case, greater temperature somewhere in the range of 40 and 50 °C restrain the movement of methane-forming microorganisms. On the other hand, mesophilic AD can sustain high OLR, however, has a lesser metabolic rate. Ordinarily, the majority of the methanogenic organisms are mesophilic while just a couple are thermophilic. This is because thermophilic methanogens are progressively subtle to unexpected thermal changes than mesophilic methanogens. Therefore, the mesophilic temperature is more suitable for the AD process due to greater stability of the process and greater fertility in microscopic organisms (Laiq Ur Rehman *et al.*, 2019).

#### 2.10.2.2. pH

The generation of biogas involves three kinds of bacteria such as hydrolysis bacteria, i.e. bacteria responsible for fermentation and methane-producing archaea bacteria. The fermentative organisms can be active in pH between 4 - 8.5 with their ideal pH ranges from 5 to 6 while methanogenic archaea can be active in pH range between 5.5 - 8.5 with the best pH between 6.5 to 8.0. "Methane-producing" microorganisms are responsible for the generation of bicarbonate, which decrease the pH. The pH <5 kill methanogens. pH >8 is deadly for most of anaerobic organisms and outcomes are the restraint of biological activities (Laiq Ur Rehman *et al.*, 2019). The reduction of the pH may result from the increase in the concentration of VFAs, as a result of the prevalence of acid-producing bacteria in the anaerobic system (Wiesmann *et al.,* 2007). The reduced pH will lessen the action of the methanogens; thus, diminishing their utilization of acetic acid and hydrogen ($H_2$), causing a further build-up of VFAs and a further decline in the pH (Basitere, 2017). When these conditions are left uncorrected, the outcome is a sudden reduction of the pH, the build-up of higher molecular weight VFAs, and cessation of the methanogenesis (Wiesmann *et al.*, 2007).

#### 2.10.2.3. Relationship between alkalinity and pH

The pH is not only linked to the alkalinity but also the acidity. Thus, the pH is a parameter that illustrates either the level of acidity or alkalinity of a medium or substance. In any biological reactor, pH impacts enzymatic movement, therefore, adequate potential hydrogen for methane forming microbe ranges from 6.8 to 7.2 (Gerardi, 2003). The accumulation of VFAs at first diminishes the potential hydrogen of the AD, which brings an increase in both alkalinity and pH, and at last the steadiness of the bioreactor (Gerardi, 2003; Basitere, 2017). At the point when the anaerobic reactor is working ideally at a pH scope of 6.8 - 7.2, the methanogens use the VFA to produce biogas (Gerardi, 2003). During the formation of biogas, the carbon dioxide ($CO_2$) content has an impact in the potential hydrogen of the anaerobic reactor as $CO_2$ can give $H_2CO_3$, $CO_2^-$ and $HCO_3^-$. The reliability of an anaerobic system is hence improved by elevated alkalinity concentration inside the biological reactor. All things considered, the bioreactor failure will occur if there is a diminution in alkalinity underneath standard operating conditions (Gerardi, 2003; Basitere, 2017).

#### 2.10.2.4. Relationship between VFA/alkalinity

To monitor an anaerobic reactor by knowing if it is stable or not, the need for knowing the ratio of VFA/alkalinity is very crucial. A ratio of VFA/alkalinity lesser than 0.3 implies the stability of a system operation but when VFA/alkalinity proportion is comprising between 0.3 to 0.4, it indicates that the system is unstable and that it needs correction. A blockage of methanogens occurs when the ratio of VFA/alkalinity goes above 0.8 which can be explained by the build-up of VFA in the reactor which leads to acidification of the reactor and makes it not appropriate for methanogens (Basitere *et al.*, 2017).

#### 2.10.2.5. Carbon: Nitrogen proportion in the feed wastewater

Correct composition of carbon and nitrogen is necessary for a productive AD. For the development of anaerobic microorganism, carbon and nitrogen are both indispensable. The use of carbon is for energy source while nitrogen is indispensable for the build-up of cellular structures and synthesis of proteins, which thusly could be changed over into $NH_3$ (ammonia), a buffer compound for the deactivation of the acidification procedure. Hence, every wastewater ought to contain nutrients and vital trace elements for the efficient AD process. Bacteria during AD devours carbon 25 to 30 times quicker than nitrogen. Therefore, to meet this prerequisite, bacteria need a 20–30:1 proportion of C to N with the biggest level of the carbon in the form of organic matter being promptly degradable (Lohani & Havukainen, 2018; Laiq Ur Rehman *et al.*, 2019). Also, Lohani & Havukainen (2018) found that a C: N:P proportion of 100:3:1 is appropriate for high $CH_4$ (methane) yield.

#### 2.10.2.6. Organic loading rate (OLR)

In the biological process, the level of deprivation of microscopic organisms is reliant on OLR. At a high OLR, a quick microbial development (yet inebriation may happen with high amounts of organic matter) happens while at a low OLR organism starvation happens. Higher OLR brings about higher biogas yield, however, a lot of maintenance time is required for complete change and assimilation of organic matter by the microbes. Likewise, supplying an excessive amount of volatile solids (VSs) into reactor will bring about higher generation and accumulation of volatile acids (VAs) which influence potential hydrogen (pH) and alkalinity of the AD. Be that as it may, if the functional OLR is excessively high, the organism couldn't go through all formed organic acids and this causes the acidification of the reactor (Lohani & Havukainen, 2018;

Fujishima *et al.*, 2000). The OLR can be calculated using Eq. 2.2 (A. Cruz-Salomón *et al.*, 2019):

$$OLR = \frac{Q \times COD}{V} = \frac{CODin}{HRT} \quad 2.2$$

Where: OLR is organic loading rate in kg COD/m$^3$·d; Q is the volumetric flow rate in m$^3$/d; COD is chemical oxygen demand in kg COD/m$^3$; V is the volume of the biological reactor also called working volume ($V_w$) and HRT is the hydraulic retention time in days or hours.

#### 2.10.2.7. Retention times (HRT and SRT)

The HRT is the normal time that liquid/wastewater stays in a biological reactor. The SRT is more important and relates to the development of the biomass. This development of the biomass due to long SRT leads to short HRTs, which translates to high rate treatment. As such, the HRT depends on the duration of the SRT. To improve HRT is important to consider the sort of wastewater and OLR; typically, a couple of days or weeks are essential. On account of low-quality wastewater, the HRT from 4.8 to 48 hours and high-quality wastewater, the HRT can be as long as 240 hours (10 days) (A. Cruz-Salomón *et al.,* 2019). The HRT can be determined using this equation (A. Cruz-Salomón *et al.*, 2019):

$$HRT = \frac{V}{Q} \quad 2.3$$

Where: HRT is hydraulic retention time in hours or days; V is the volume of the reactor or $V_w$ is working volume of the reactor in m$^3$ and Q is the volumetric flow rate in m$^3$/d.

The sludge retention time (SRT) is an operating and significant parameter that influences the biochemical and physical qualities of the anaerobic granular sludge (AGS). The operation of a successful AD system such as the EGSB reactor relies for the most part upon the SRT, which is the essential aspect that dictates the activity of hydrolytic and methanogenic organisms introduced in the EGSB under various temperature conditions. To hold an adequate quantity of methanogenic microscopic organisms in the biological reactor, it is important to keep the SRT at steady state for the proliferation of the methanogenic bacteria. This culminates in the development of the AGS with an adequate degree of methanogenic archaea. Overall, the SRT must be kept up 2 to 3 times over the proliferation period of the microorganisms to maintain the operation at steady state (A. Cruz-Salomón *et al.*, 2019).

### 2.10.3. Types of anaerobic digesters

#### 2.10.3.1. Low-rate anaerobic processes (LRAPs)

LRAPs are slurry biological reactors that use a combination of solids sedimentation and build-up to expand the SRT with respect to the HRT. Mixing is commonly by the expansion of influent wastewater and by methane gas production. As an outcome, all around blended conditions are not entirely provided and SS settle and gather in the biological reactor (Njoya, 2019). A few systems have fused settled solids reuse from a downstream settling zone to an upstream response zone. Truly, materials in the wastewater are permitted to buoy to the surface and conglomerate in a scum that gives some protection and odour control, i.e. to prevent the biogas to flow through it and be released in to the air. Environmental conditions inside LRAPs are not the most suitable and, even though active biomass aggregates, exact control of the SRT isn't entirely possible. HRTs in the >5 day range are frequently appropriate. OLR of 1 to 2 kg COD/ ($m^3$. day) are regularly observed to be suitable (Grady *et al.*, 2011; Njoya *et al.*, 2019).

### 2.10.3.2. High-rate anaerobic processes (HRAPs)

HRAPs are biological reactors that give important retention of active biomass, bringing about huge contrasts between SRT and HRT. Three instruments are utilized to hold biomass such as the development of settleable particles that are sedimented, the utilization of reactor designs that hold SS, and the development of biofilms on surfaces inside the biological reactor. In numerous examples, more than one system is working inside the biological reactor (Njoya *et al.*, 2019). Subsequently, HRAPs speak to a range of biological reactor types running from suspended development to attached development, with hybrid biological reactors, which contain amounts of both suspended and appended biomass, in the middle. An example of a typical HRAP performance is presented in Table 2.6 below (Grady *et al.*, 2011; *Njoya et al.*, 2019).

**Table 2. 3:** Example of typical HRAP performance (Grady *et al.,* 2011).

| **Parameter** | **units** | **data** |
|---|---|---|
| $BOD_5$ removal | % | 80-90 |
| COD removal | g | 1.50 x $BOD_5$ removed |
| biogas produced | $m^3$/kg COD removed | 0.5 |
| Methane produced | $m^3$/kg COD removed | 0.35 |
| biomass produced | g VSS/g COD removed | 0.050 to 0.100 |

## 2.11. Expanded granular sludge bed reactor (EGSB)

An upgraded configuration of the up-flow anaerobic sludge blanket (UASB) is the EGSB see Figure 2.2. This biological reactor promotes improved mixing through its height. The effluent which is recycled entails bed’s expansion and encourages better contact between the wastewater and the biomass (Bhattacharyya & Singh, 2009). This digester is cost-effective, efficient and a progressively famous innovation since it works utilizing a fluidized bed, which permits expanding in the carbon-based load and it improves cell maintenance, producing higher treatment efficiencies which goes up to 95 % while generating biogas (A Cruz-Salomón *et al.*, 2019). The productivity of this biological reactor fundamentally relies upon the conditions of operation. It shows qualities such as improved flow rate and shorter HRTs (Evren *et al.*, 2012; Rajakumar *et al.*, 2011).

The performance of the EGSB has improved in terms of the removal of COD from the treated wastewater. Zhang *et al.,* (2008) stated that EGSB removed up to 91% of COD for HRT of 2 days with OLR of 80g sCOD/L while for the same reactor, Basitere *et al.*, (2016) reported that COD removal was 55% with maximum OLR of 1gCOD/L.day for an HRT of 3 days and recently Williams (2017) removed up to 93% tCOD at average HRT of 2.4 days and OLR of 2g tCOD/L.day.

Additionally, Sheldon & Erdogan (2016) reported that EGSB removed up to 93% tCOD at an HRT of 12 hours with an up-flow velocity ($V_{up}$) of 0.85m/h and an OLR of 11 kg COD/$m^3$.d with the system treating soft drink wastewater.

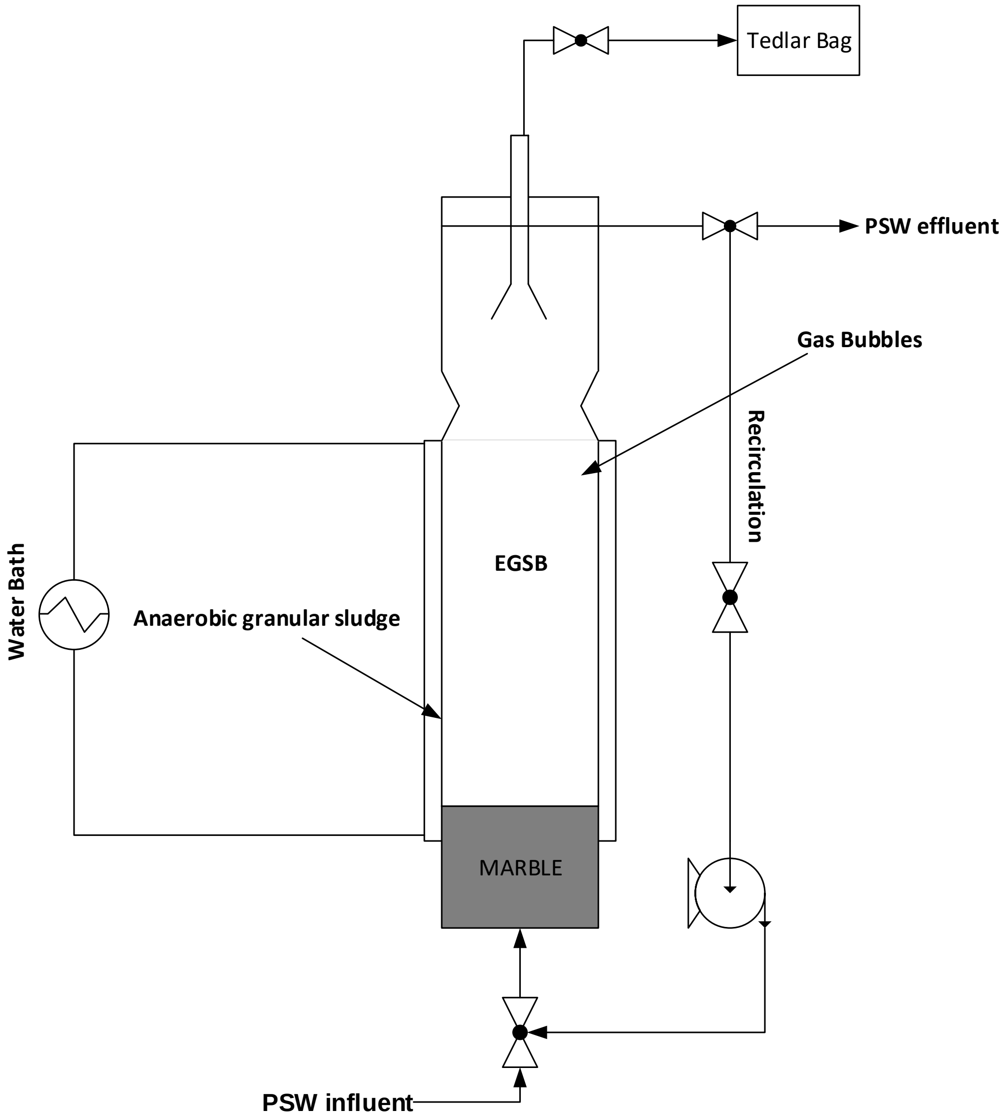


**Figure 2. 2:** Schematic representation of an EGSB reactor.

**Table 2. 4:** Principal characteristics of EGSB bioreactor (Zhang *et al.,* 2008; A. Cruz-Salomón *et al.*, 2019).

| Description | Parameter | Performance |
|---|---|---|
| EGSB reactor | Up-flow Velocity (Vup) | 3-30m/h |
| | OLR | < 40 Kg COD/$m^3$ h |
| | Height/diameter proportion | 10:1 up to 25:1 |
| | HRT | 4.8h to 48h for low-quality wastewater; up to 240h (10days) for high-quality wastewater |
| | Start-up times | 30 - 60days |
| | AGS expansion's bed | the total height of the biological reactor up to 60% |
| | Removal efficiency | up to 90% |

### 2.11.1. Advantages of the EGSB reactor

The points of interest reported in this section are a portion of the operational properties for the EGSB bioreactor. The EGSB is characterised by (Zhang *et al.,* 2008; A. Cruz-Salomón *et al.*, 2019):

- Closed system entirely
- Zero release of odour
- Better anaerobic granular sludge-wastewater contact
- Granular sludge with good settle-ability
- low-cost of operation
- low chemicals and nutrients requirement
- the design is compact (appropriate for lesser spaces)
- the production of AGS is low
- high potential to produce biogas or bio-methane.

### 2.11.2. Disadvantages of EGSB reactor

The disadvantages associated to the EGSB bioreactor are as follows (Zhang *et al.,* 2008; A. Cruz-Salomón *et al.*, 2019):

- Due to high $V_{up,}$ the aptitude to eliminate particulate organic matter is reduced,
- The granular bed reactor does not retain suspended solids which means the suspended solids leaves with the wastewater to the next unit, and
- The reduction of granule activity leads to high sludge washout.

## 2.12. Summary

This chapter gives information applicable to the significance of treating PSW and a general idea of its features. AD is exhibited as an appropriate choice for the treatment of PSW particular in an EGSB. The process offers minimal cost, alongside the benefits of being a process which minimizes the amount of sludge produced, taking into consideration the creation of bio-methane, an alternative source of energy. An explanation of AD and its driving parameters followed by the different types of anaerobic digesters as well as the EGSB, its characteristics and advantages and disadvantages, are presented.

# CHAPTER 3

# Treatment of Poultry Slaughterhouse Wastewater (PSW) Using a Pretreatment Stage, an Expanded Granular Sludge Bed Reactor (EGSB), and a Membrane Bioreactor (MBR)

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Supplementary figure is provided in the Appendix A.

# Chapter 3: Treatment of Poultry Slaughterhouse Wastewater (PSW) Using a Pretreatment Stage, an Expanded Granular Sludge Bed Reactor (EGSB), and a Membrane Bioreactor (MBR)

### 3.1. Introduction

The contamination of clean water sources contributes to the global water crisis. Therefore, the treatment and reuse of wastewater is indispensable. Additionally, adequate management of water sources is critical in semiarid and dry regions of countries such as South Africa (SA) (Kasiri *et al.,* 2012;Mpentshu, 2018). To protect both amphibian and earthbound living animals, the wastewater needs to be treated effectively before discharging it into freshwater sources (Bustillo-Lecompte & Mehrvar, 2017; Rinquest *et al.*, 2019). The quality of wastewater generated from various industrial facilities depends on prevailing operations in those industries and the quantity of contaminants produced during these operations(Njoya, 2019). Depending on the characteristics of the given industrial wastewater, various methods can be used for its treatment. Therefore, biological treatment is deemed the most suitable for wastewater laden with high organic matter, suspended solids, fats, oil, and grease (FOG), macronutrients, and pathogens (Gerardi, 2003;Njoya *et al.*, 2019). In this regard, the treatment of poultry slaughterhouse wastewater (PSW), which is the primary focus of this study, can, therefore, be efficiently treated using a biological system (Avula *et al.*, 2009;Del Nery *et al.*, 2001). Pollutants in the PSW, if discharged untreated to the environment, can cause eutrophication and deoxygenation of receiving water bodies, which can harm the health of humans, animals, and plants. Therefore, it is important to treat such wastewater before it is discharged into the environment (Bustillo-Lecompte & Mehrvar, 2017;Yaakob *et al.*, 2018). SA is currently experiencing challenges associated with water shortages, which the poultry industry (producing 1.93 million metric tons in chicken meat in SA for the year 2020) could solve by developing advanced treatment processes to treat the wastewater produced to meet national legislation and municipal discharge standards, including local government regulations. These regulations are implemented such that sustainable wastewater treatment technologies are developed and used to lessen potable water usage while protecting the environment. This motivated several industries to devise new methods of water reclamation to lessen reliance on currently available water resources (Basitere *et al*., 2016;Williams, 2017) . Several recent studies investigated the treatment of PSW using biological systems. One of these studies encountered challenges when an expanded granular sludge bed reactor (EGSB) combined with anoxic–aerobic tanks was used, whereby the system experienced sludge washout when the influent had high FOG and a high suspended loading rate (SLR) (Basitere *et al*., 2016). Furthermore, a similar study was done by Sheldon & Erdogan, (2016), who reported that an EGSB coupled with a membrane bioreactor (MBR) achieved excellent results for treating soft-drink industry wastewater, removing most of the contaminants, including macronutrients, when the EGSB was used as a primary biological treatment unit. This culminated in this research study, which focuses on treating PSW using a pretreatment stage–EGSB–MBR system. Similarly, Zhang *et al*., (2008) achieved a 91% total chemical oxygen demand (tCOD) removal rate at a hydraulic retention time (HRT) of 48 h and an organic loading rate (OLR) of 17.5 kg COD/m3 ·day at an average operating temperature of 35 ◦C using an EGSB, although the system was designed for treating palm-oil mill effluent. This system was not coupled with an MBR. Due to financial constraints and a lack of promotion of advanced and affordable wastewater treatment options in SA, particularly for PSW, there is an urgent need to develop effective and low-cost solutions for high-strength wastewater treatment, particularly PSW. This study was aimed at investigating the effectiveness and performance of using a miniaturized lab-scale plant consisting of a pretreatment stage and an EGSB coupled with a MBR, for wastewater treatment by poultry slaughterhouses globally.

### 3.2. Objectives

The objectives of this section was to:

- Determine the performance of the pre-treatment stage with respect to pollutant removal.
- Determine the performance of the EGSB in terms of pollutant removal.
- Determine the performance of the MBR in terms of pollutant removal.
- Determine the overall system (pre-treatment-EGSB-MBR) performance in terms of pollutant removal.
- Determine if the final effluent from the MBR unit meet the CoCT industrial discharge standards.

### 3.3. Materials and Methods

#### 3.3.1. Poultry Slaughterhouse Wastewater (PSW) Sampling

The PSW used in this study was collected from a poultry slaughterhouse situated in the Western Cape province of SA. The poultry slaughterhouse processes a large quantity of birds, which in turn generates a large quantity of PSW (Haandel; & Lubbe, 2012). The PSW generated comes from numerous processes (killing, bleeding, scalding, defeathering, etc.) and is partly treated onsite to meet the City of Cape Town (CoCT) discharge standards (Njoya *et al.*, 2020). The PSW collected was sampled during peak production using 25 L polypropylene containers and stored in a refrigerator at 5 ◦C to minimize acidification. The sampling of the PSW was done 3 days a week and used as a feed to the miniaturized lab-scale plant designed.

### 3.3.2. EcoflushTM—A Supplementation Agent for the Pretreatment Stage

Ecoflush™ is a commercial product that is supplied in SA by Mavu biotechnologies (Pty) Ltd. as an assemblage of consortia producing hydrolases. The microorganisms were isolated from soil and subsequently grown and stored in a physiologically dormant state. When exposed to a rich organic source, such as PSW, they are resuscitated to produce enzymes primarily for FOG hydrolysis. The product also contains glaucids and fundamental amino acids that invigorate the natural tendency of specific microorganisms to produce enzymes associated with the hydrolysis of hydrocarbon constituents constituting the organic matter. Ecoflush™ also oxidizes $NH_3$ into $NO_3{}^-$ and $NO_2{}^-$. It also eliminates $NH_3$, including odor-producing organisms, while rapidly diminishing the population of pathogenic microbes (Ergofito, 2019). Ecoflush™ weakens the hydrocarbon chains in FOG and complements other organisms that are prevalent in high-strength wastewater while reducing $H_2S$-producing microorganisms, thereby rapidly decreasing odor(Ergofito, 2019).

### 3.3.3. Operation of the Pretreatment–EGSB–MBR System

The PSW treatment system consisted of a biological pretreatment stage whereby raw PSW was mixed with EcoflushTM for biodelipidation before the PSW entered a holding feed tank used to supply the PSW to the EGSB as a primary organic matter removal system. The two stages were coupled with an MBR as the final treatment stage for a reduction in residual organic matter and total suspended solids (see Figure 3.1).


**Figure 3. 1**: Poultry slaughterhouse wastewater (PSW) miniaturized lab-scale plant setup.

### 3.3.4. Pretreatment Tank Preparation

A mixture of the Ecoflush$^{TM}$ (20 mL) and ~20 L of raw PSW (0.1% v/v) was used in the pretreatment tank for a reduction in FOG through biodelipidation and to induce biofloculation of suspended particles. For the activation of the microbial community in the EcoflushTM-supplemented pretreatment tank, the mixture was aerated by air stone spargers for 24 h at room temperature. After aeration, the air sparging was stopped such that the aggregated FOG and suspended solids were flocculated, before the PSW entered the feed tank (holding tank) of the EGSB. The PSW in the holding tank was analyzed for dissolved oxygen (DO), FOG, potential of hydrogen (pH), COD, electrical conductivity (EC), total dissolved solids (TDS), and total suspended solids (TSS). The PSW was thereafter fed to the EGSB.

### 3.3.5. EGSB Reactor System Used

The EGSB material of construction was a clear cylindrical polyvinyl chloride (PVC) column with a tapered bottom and a working volume of 2 L. The height was 0.6119 m with an internal diameter of 0.11 m. Ceramic marbles (0.0814 m) were used as packing material for the underdrain of the EGSB for sludge retainment. The recycle on the EGSB was utilized to regulate the PSW up-flow velocity of 0.1 m/h and bed expansion inside the EGSB, to prevent clogging of the underdrain in the bioreactor, and to better mix both the PSW and the sludge (Kaskote *et al*., 2019) . The EGSB was fed with PSW from the bottom using the Antech aspendose A 5.1L/0.5B peristaltic pump purchased from Enelsa in Turkey, Antalya. The product coming from the EGSB was sampled using 2 L polypropylene bottles subsequent to analyses. The EGSB was operated at a range of 35–37 ◦C, with the temperature being maintained using a heating jacket connected to a water bath maintained at 37 ◦C. To reduce heat loss to the environment, the EGSB was insulated (see Figure 3.2).

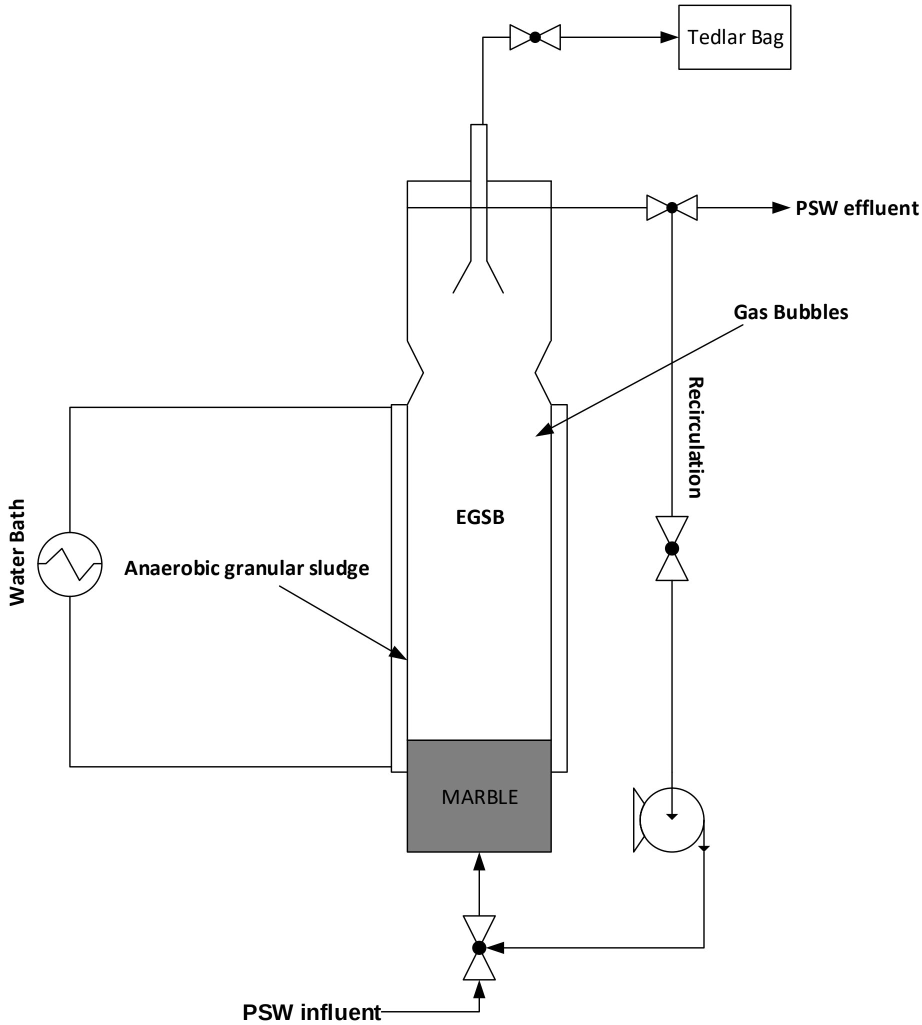



**Figure 3. 2**: Schematic representation of the EGSB used.

### 3.3.6. Inoculation of the EGSB

The inoculation of the EGSB was done by first putting the underdrain, followed by the addition of 0.4 L of activated sludge that was sampled from an anaerobic reactor in operation at the South African Breweries (Newlands, South Africa); thereafter, 1.6 L of raw PSW was added to the EGSB. The PSW, which was kept in a fridge at 5 °C, was incubated at 37 °C prior to use. Thereafter, six cups of Nestle Lactogen starter infant formula powdered milk were added to 400 mL of sterile distilled water to prepare a milk solution, with 200 mL of the milk solution being added as an organic source to sustain the sludge microbes for rapid growth (Rinquest *et al*., 2019).

### 3.3.7. Operating Conditions of the EGSB

The EGSB was kept at 35–37 ◦C during the 77 days of operation. The pretreated PSW in the holding tank was fed to the EGSB after 72 h of inoculation (stagnation period without PSW supplementation) to allow the volatile organic compounds (VOCs) to dissipate from the bioreactor mixture, as well as for DO reduction before the PSW was fed to the reactor (Mukandi, 2017). The EGSB was run using a batch-fed strategy of PSW supply for 4 h/day for 7 days for microbial acclimatization, in order for the microbes to familiarize themselves with the PSW. This was done to achieve microbial growth, as the microbes in the EGSB needed nutrients for them to grow; after that acclimatization period, the bioreactor was run continuously throughout the study. The EGSB feed flow rate was 0.35L/h with a hydraulic retention time (HRT) of 5.71 h, which was kept constant throughout the study.

### 3.3.8. Membrane Bioreactor (MBR) Used

The MBR unit used had a rectangular container (working volume of 120.51 L) with embedded membranes within it. For the MBR, NADIR® UP150membraneswereused. The membranes were composed of a hydrophilic polyether-sulfone (PES) sheet with a nominal pore size of ~0.04 µm, operated in a dead-end filtration mode (see Figures 3.3 and 3.4). Inside the MBR unit, there was a mesh to cover the membranes to avoid clogging of the MBR unit by washout material from the EGSB. Sodium metabisulfite (SMBS) was used to preserve the membranes to avoiding microbial growth. The HRT was controlled by the Antech aspendose A 5.1L/0.5B peristaltic pump purchased from Enelsa in Turkey, Antalya. For aeration, a Regent® RE-9500 air pump (Dolphin pumps, Cairo, GA, USA) was used to supply air into the MBR unit. A simultaneous nitrification and aerobic nitrification (SaND) compartment, as reported by Rinquest *et al.*, (2019), was incorporated within the setup.


**Figure 3. 3**: The MBR unit used.

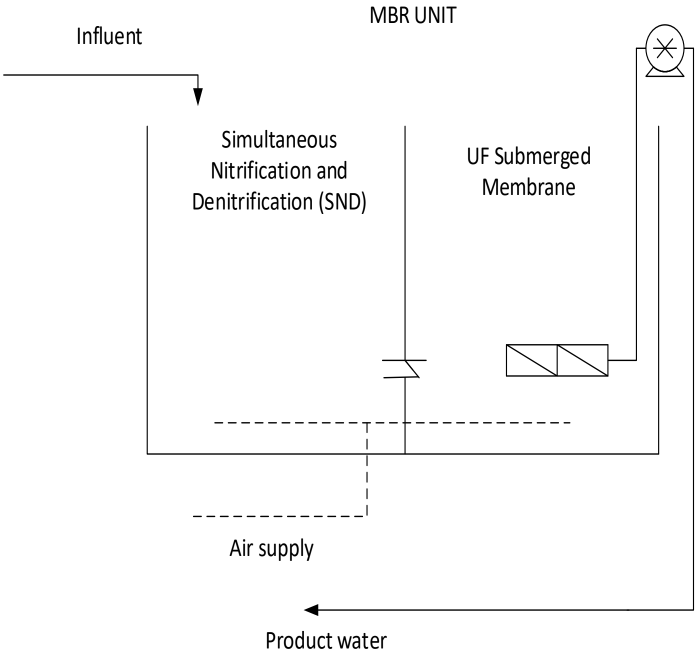



**Figure 3. 4**: Schematic representation of the MBR unit used.

**3.3.9. Inoculation and Operating Conditions of the Membrane Bioreactor (MBR)**

The inoculation of the MBR unit was done by introducing 90 mL of the Ecoflush$^{TM}$, followed by 90 L of water and 10 L of raw PSW (see figure 3.5). the acclimatization period took 3 days; then, the EGSB effluent was introduced as feed into the MBR unit. Parameters such as temperature, pH, TDS, conductivity, and DO were measured within the MBR.

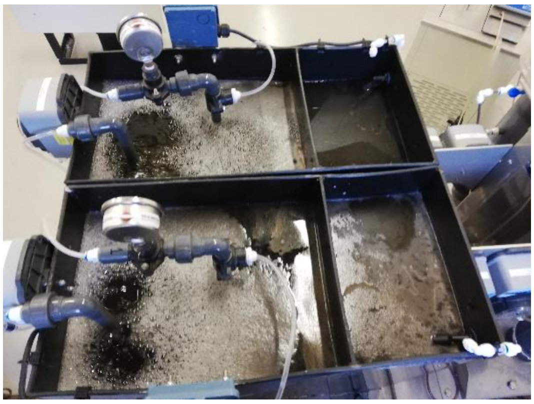


**Figure 3. 5**: The MBR unit with a membrane compartment and an SNaD during inoculation.

### 3.3.10. Sample Collection and Analyses for the Lab-Scale Plant

Throughout the study, a volume of either treated or untreated (to be fed to another unit) wastewater was analyzed for temperature, pH, COD, biological oxygen demand (BOD), electric conductivity, alkalinity (CaCO3), fats, oil, and grease (FOG), total dissolved solids (TDS), total suspended solids (TSS), dissolved oxygen (DO), and volatile fatty acids (VFAs) (Apha, 2005;A. Cruz-Salomón *et al*., 2019).

### 3.3.11. Analytical Methods for the Lab-Scale Plant Samples

All samples were analyzed for characteristic parameters at the CoCT scientific services laboratory, according to the standardized American Public Health Association (APHA) methods (Apha, 2005).

## 3.4. Results and Discussion

### 3.4.1. Pretreatment Stage Performance

Figure 3.6 presents the PSW quality characteristics from the pretreatment stage, accounting for fluctuations in the percentage removal determined from concentrations of TSS, FOG, and COD at the inlet and outlet. It was observed that the quality of the PSW feed and product fluctuated considerably, with a noticeably high concentration of the COD, TSS, and FOG on the 70th day of operation. This was attributed to various factors, including a significant change in the quality of the PSW fed to the pretreatment stage. This change could be directly related to the prevailing activity in the poultry slaughterhouse at the time of the sample collection, as a result of which the PSW may have contained more organic matter than normal. To assess the distribution of the sampling points with respect to the COD, FOG, and TSS, a boxplot was plotted, as illustrated in Figure 3.7, from which outliers can be noticed for each of the parameters for both the feed and the product of the PSW pretreatment stage. To correct the distribution of these data points and remove the noise from the data, various data processing techniques can be used such as the evaluation of the Z-score, the use of a standard scaler, or the application of the interquartile rule to identify and replace/delete outliers. The interquartile rule was selected for this study. Furthermore, the outliers were replaced instead of being deleted due to the size of the dataset. The outlier identification and replacement using the interquartile rule resulted in the distribution provided in Figure 3.7 (a) and (b), from which a distribution was smoothed with the replacement of the outliers with the median value of each parameter evaluated.

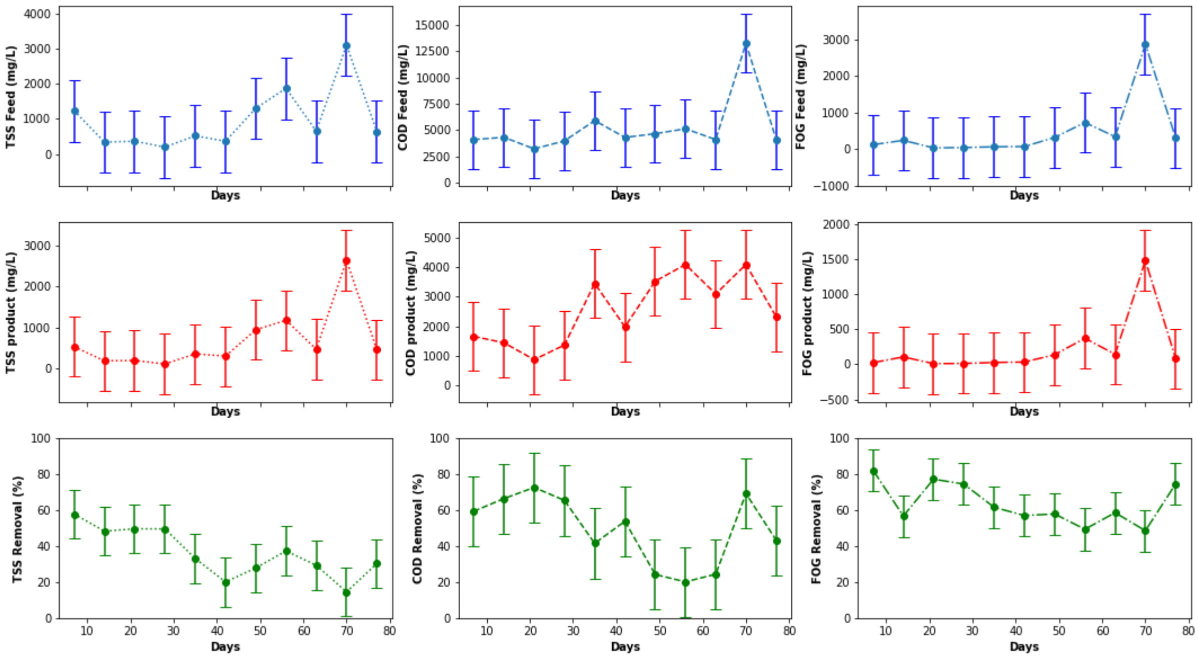
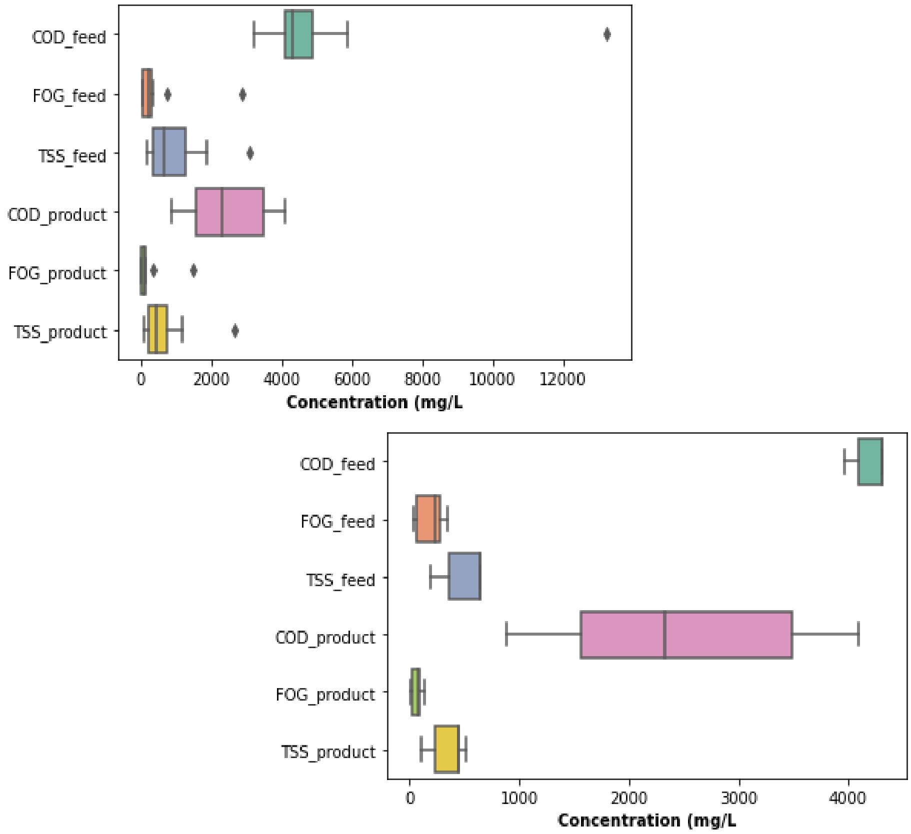



**Figure 3. 6**: Pretreatment stage performance determined using COD, TSS, and FOG removal.




(a) Boxplot before outliers replacement (b) Boxplot after outliers replacement

**Figure 3. 7**: Boxplots of the distributions of TSS, FOD, and COD before and after outlier replacement.

As illustrated in Figure 3.8, the peaks noticed for the inlet FOG, TSS, and COD in Figure 3.6 were eliminated and, thus, contributed to a reduction in the data distribution range for better analysis in order to elucidate a clear representation of the features of the PSW pretreatment. As observed in Figure 3.8, the pretreatment stage had an FOG removal of 55% to 85%. In addition to the pretreatment tank, the employment of star screens can contribute to the removal of a significant quantity of floating fats contained in the PSW. Furthermore, the pretreatment stage contributed significantly COD and TSS reduction, whereby the percentage removal oscillated between 20% and 50% for TSS and 10% and 80% for the COD. A further reduction in these wastewater quality characteristics can be improved with a further treatment process, i.e., biological treatment, thus motivating the use of the EGSB and the MBR.

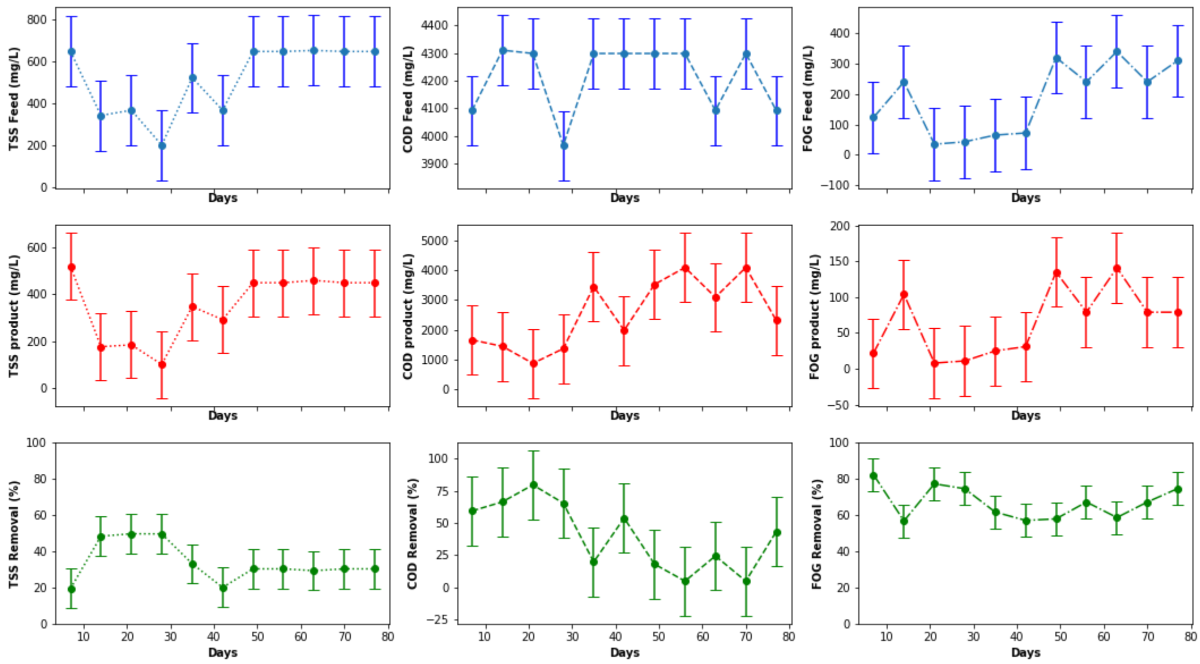



**Figure 3. 8**: Pretreatment stage performance assessed using COD, TSS, and FOG concentration removal.

### 3.4.2. Expanded Granular Sludge Bed Reactor (EGSB) Performance

Before evaluating the performance of the EGSB in terms of COD, TSS, and FOG removal, as displayed in Figure 3.9, a boxplot of these values was plotted to visually detect possible outliers. The interest was specifically in the product stream generated from the EGSB, because the product would have a greater influence of the MBR performance. As illustrated in Figure 3.10, there were no outliers for the parameters quantified, including values observed for the organic loading rate (OLR). Therefore, no data processing or adjustment was required, as observed in Figure 3.9, with insignificant variations in the concentrations of the COD, TSS, and FOG in both the inlet and the outlet of the EGSB, which was attributed to the stability and performance of the pretreatment unit including the anaerobic bacteria within the anaerobic granular bed. Such a performance can be influenced by the competition between sulfate-reducing bacteria and methane-producing bacteria, including the accumulation of inhibitors within the anaerobic granular bed or other environmental factors that can prevent the anaerobic sludge granules to grow to maturity. Overall, with a consistent feed, it is possible to control most of these parameters during the anaerobic digestion stage. However, the temperature and the pH inside the bioreactor were continuously monitored and remained within the mesophilic range in terms of the temperature, while the pH fluctuated in the range 6.5 to 8. The expected performance trend for such a system would steadily increase over time, particularly for the removal of COD, TSS, and FOG.

Figures 3.11 – 3.13 demonstrate some increase in the performance of the EGSB, albeit for sporadic periods during the study. This performance did not improve even with a varied organic loading rate. Overall, the EGSB performed best for the removal of the FOG and TSS with peak removal percentages above 80%, while the bioreactor performance was low for the removal of COD, with an average 60% removal. The sporadic underperformance of the EGSB was determined not to be related to the increase in the OLR, with the overall performance trend not displaying a depreciation in the removal percentages of key parameters analyzed with an appreciation of the OLR. This observation further highlights the importance of monitoring the primary treatment system closely, especially when anaerobic digestion is used as a key driver of the overall performance of the system designed.

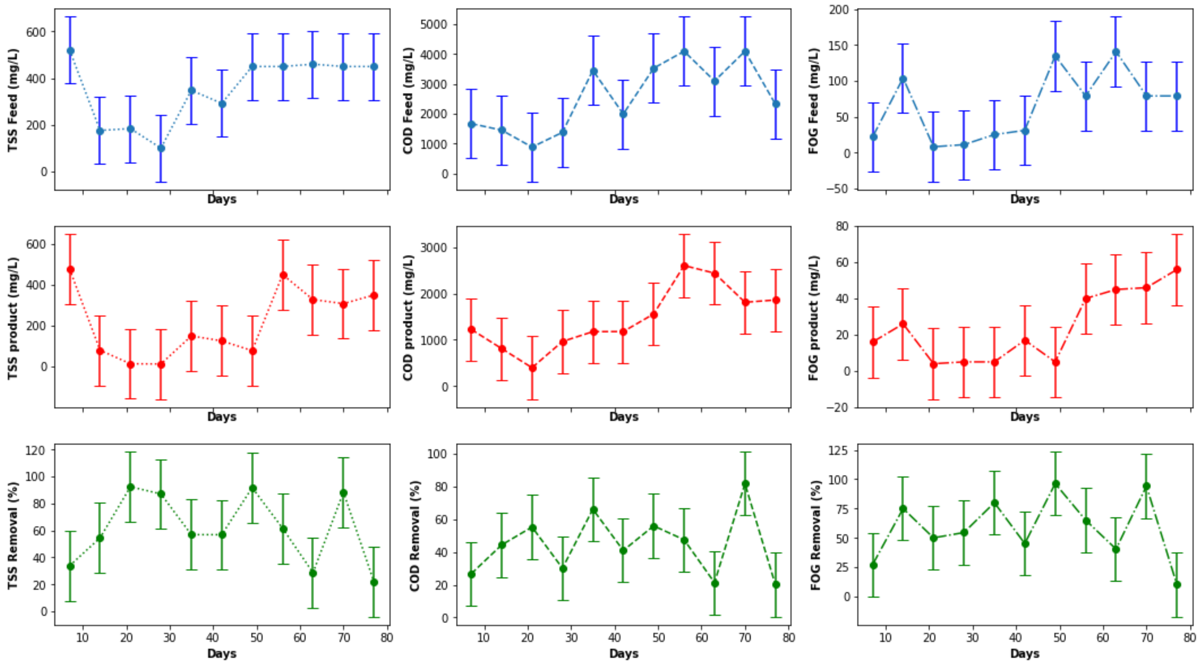



**Figure 3. 9**: EGSB performance with respect to COD, TSS, and FOG removal.

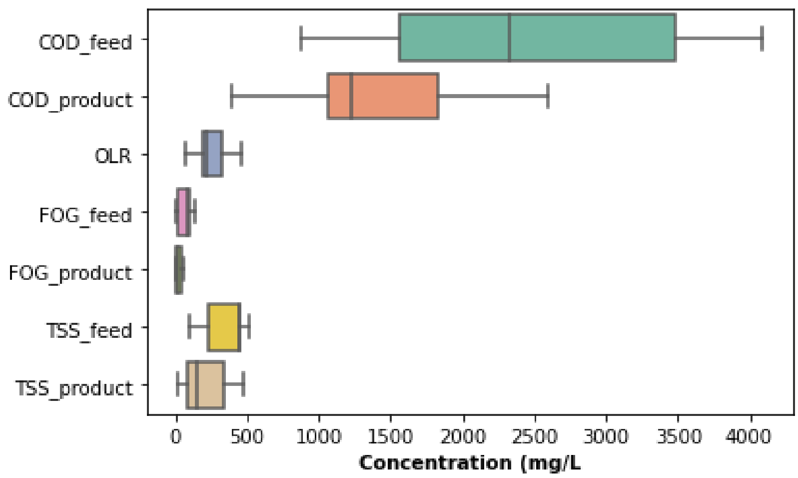



**Figure 3. 10**: Boxplot of the EGSB parameters.

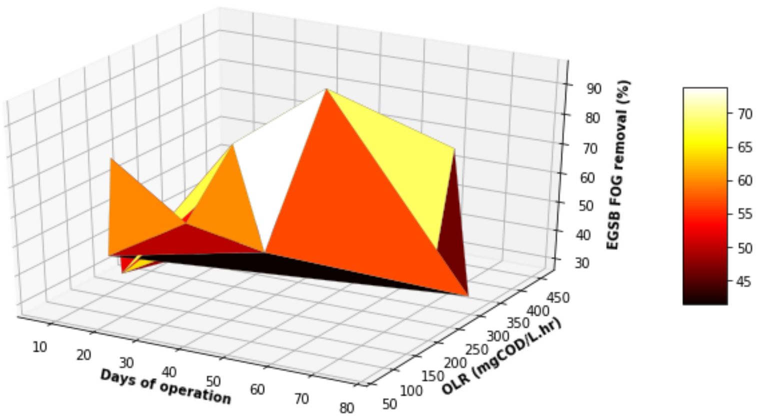



**Figure 3. 11**: Variation in FOG removal with differentiated OLR during the EGSB operational time.

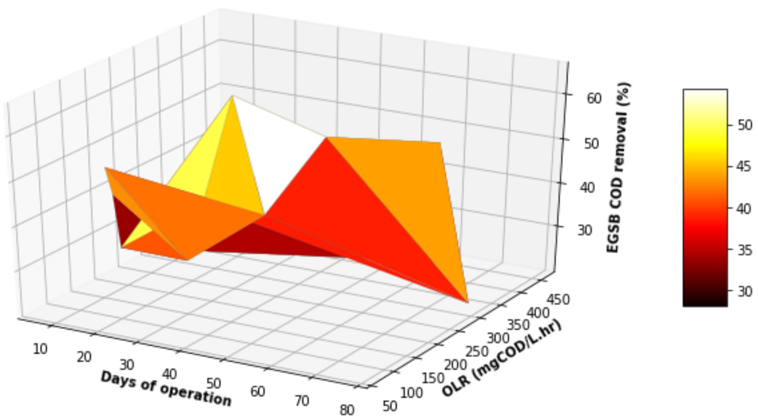



**Figure 3. 12**: Variation in COD removal with differentiated OLR during the EGSB operational time.

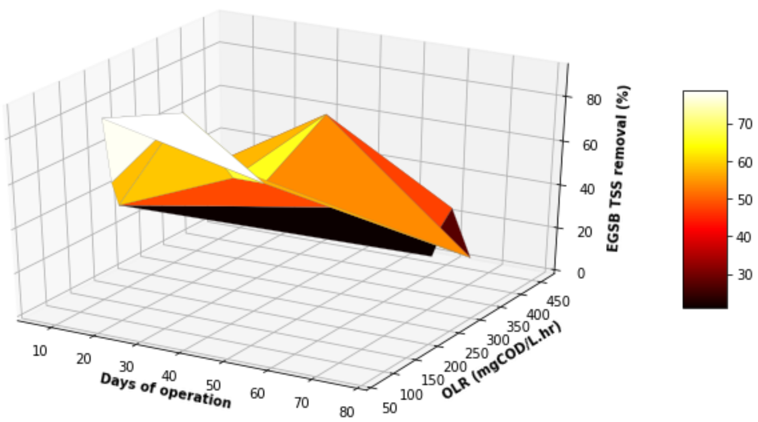



**Figure 3. 13**: Variation in TSS removal with differentiated OLR during the EGSB operational time.

### 3.4.3. Membrane Bioreactor (MBR) Performance

Figure 3.14 depicts the variation in FOG, TSS, and COD concentration in the feed and product streams of the MBR, including the percentage removal of these parameters. Due to a noticeable variation in the concentration of the parameters evaluated, an evaluation was carried out using the boxplot (Figure 3.15), which indicated that there was no outlier in each distribution. Despite a decrease in the TSS removal on the 21st and 28th days of operation, the performance of the MBR improved overtime with regard to COD and TSS removal. This trend was similar to that observed for the EGSB. The deterioration in the performance of the MBR on the 21st day of operation for the removal of the three parameters evaluated, as well as on the 28th day for TSS, was attributed to lower concentrations of contaminants in the feed to the MBR, which culminated in a lower performance because the feed was already of improved quality. However, this consistency in the performance of the MBR was not observed for FOG removal, which fluctuated between 20% and 80%, and it did not improve over time unlike that observed for TSS removal, which steadily remained above 60% with a peak at >95%. The COD removal was maintained above 75% throughout the process with a peak performance also being observed at >95%. This suggested that the structure of the membranes in the MBR was more suited to removing suspended solids and other nutrients than FOG, which was solubilized by the Ecoflush™ used, suggesting seepage of solubilized FOG through the membranes. This assertion requires further investigation.

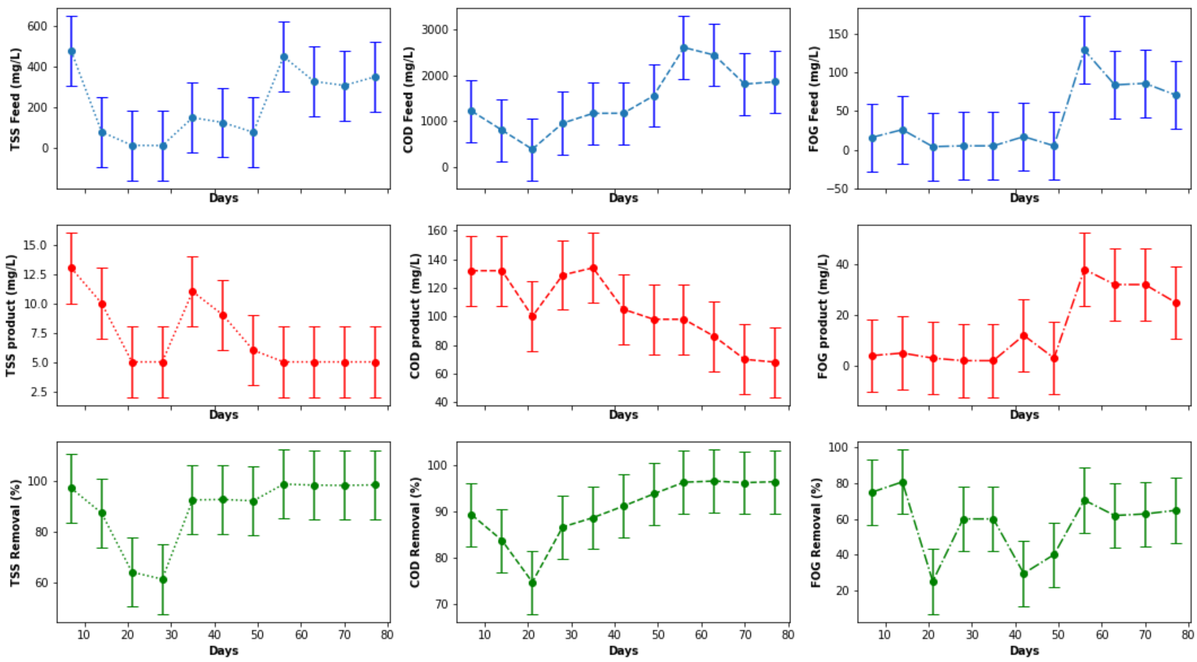



**Figure 3. 14**: MBR performance with respect to COD, TSS, and FOG removal.

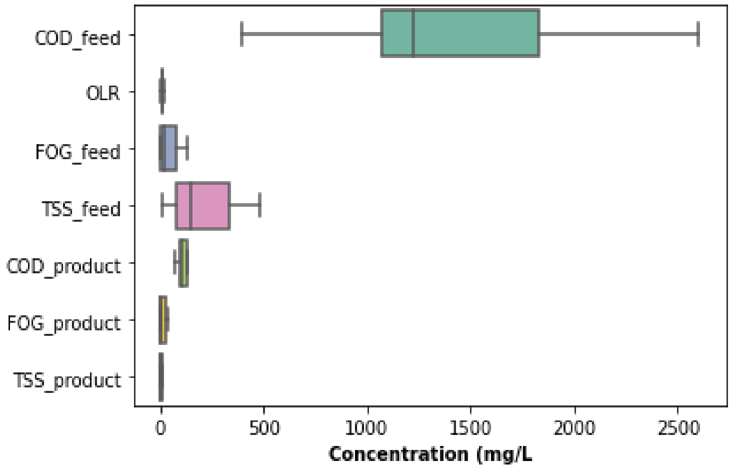



**Figure 3. 15**: Boxplot of the MBR performance with regard to quantified quality parameters.

Figures 3.16 – 3.18 provide a further evaluation of the performance of the MBR in terms of TSS, FOG, and COD removal with respect to the operating time and variation in the OLR to the system. It was observed that the range of the OLR was much less than that determined in the feed to the EGSB. This was attributed to a good performance of the EGSB that provided a feed with less organic matter to the MBR. These factors led to a more stable performance of the MBR system, even with fluctuation in the OLR throughout the experiment. The performance of the MBR was of significance and highly contributed to the overall performance of the lab-scale plant.

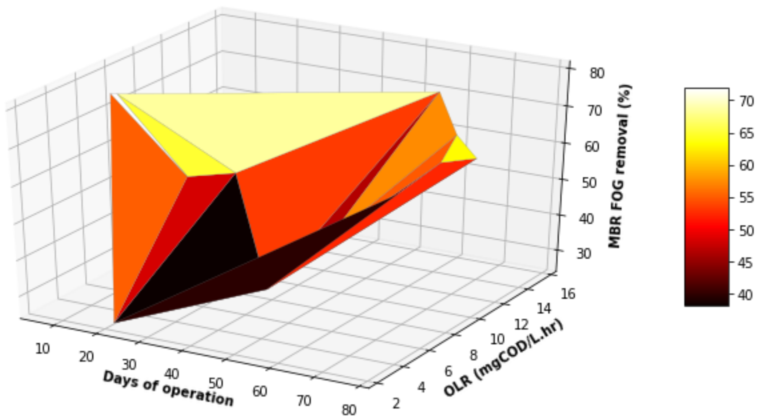



**Figure 3. 16**: Variation in FOG removal with varying OLR during the operation of the MBR.

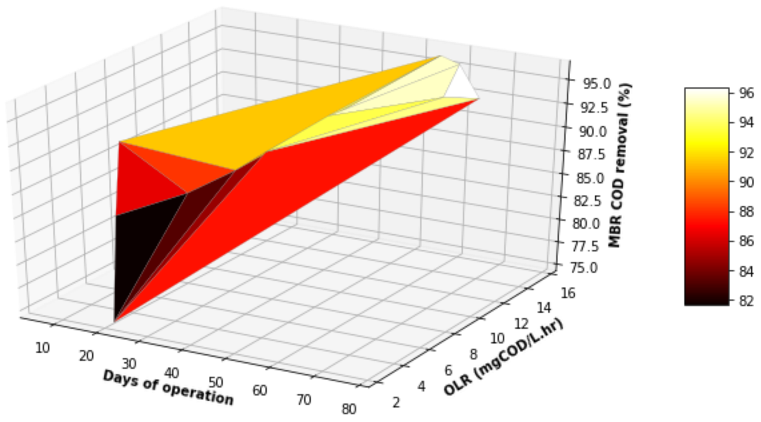



**Figure 3. 17**: Variation in COD removal with varying OLR during the operation of the MBR.

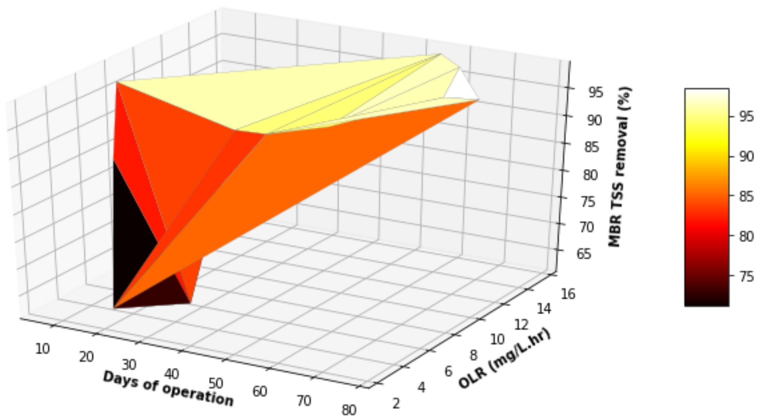



**Figure 3. 18**: Variation in TSS removal with varying OLR during the operation of the MBR.

### 3.4.4. Overall System Performance of the Pretreatment–EGSB–MBR Lab-Scale System

Figures 3.19 and 3.20 showcases that there was an absence of outliers in the distribution of the parameters investigated for the overall process, which validated the assertion that the system was stable in its operation, with minimal variations in the key water quality parameters assessed for the overall process. From Figures 3.21 and 3.22 below, it can be observed that the overall performance of the lab-scale plant varied between 97% and >99% for TSS removal, 96.5% and 99% for COD removal, and 84% and 98% for FOG removal. The overall performance of the lab-scale plant with respect to TSS and COD removal seemed more consistent when compared to FOG removal. There was demonstrable sporadic removal of the FOG percentage removal toward the end of the study; however, the overall system contributed to a significant decrease in the FOG concentration from the PSW with a concentration of less than 40 mg FOG/L in the final treated water, which is less than the limit of 400 mg FOG/L enforced by the CoCT for treated wastewater to be discharged to freshwater bodies.

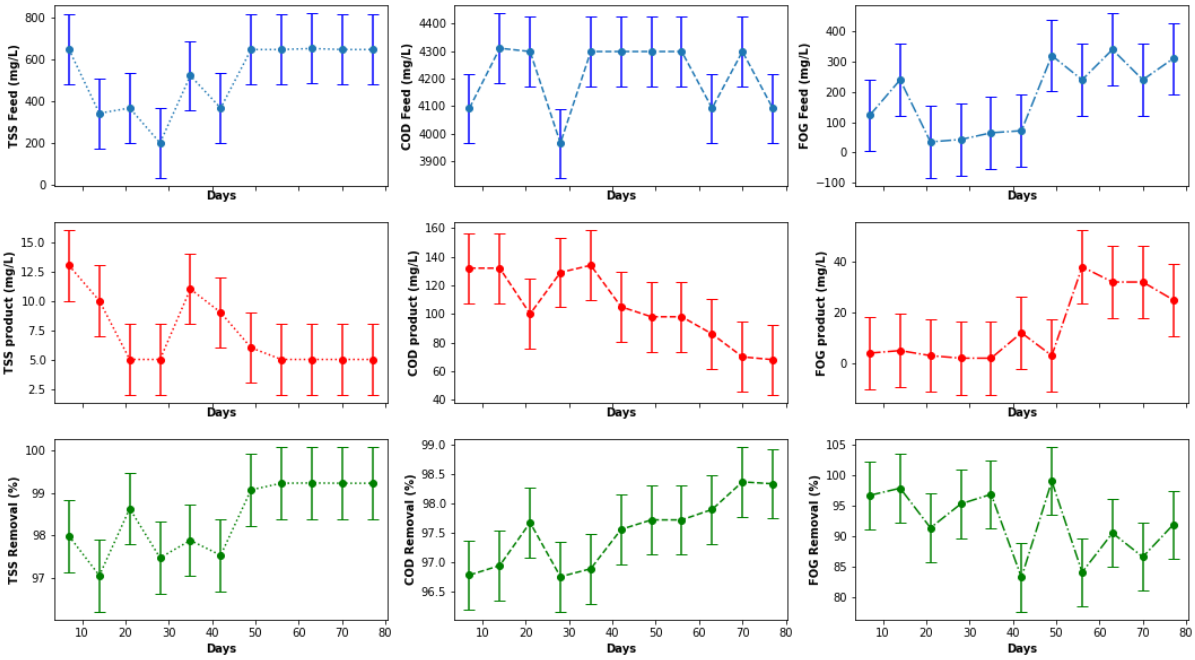



**Figure 3. 19**: Overall performance of the pretreatment–EGSB–MBR system with respect to COD, TSS, and FOG removal.

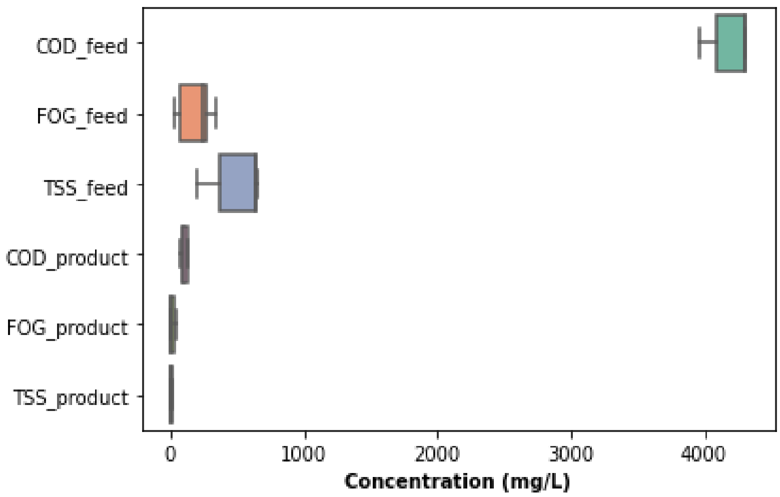



**Figure 3. 20**: Boxplots of the parameters for the overall process.

Moreover, prior to replacing the outliers in the measured parameters for this study, a more representative distribution of key quality parameters was provided for the PSW samples collected for this study. The values of COD, FOG, and TSS concentration in the collected PSW samples all exceeded the discharge limits imposed by the CoCT by-laws (see Table 3.1). Such an excessive concentration in the wastewater quality parameters could adversely contaminate the environment, especially if the PSW is not treated. The quality of the PSW was also dependent on the prevailing operations in the poultry slaughterhouse from which the PSW samples were collected. Therefore, such wastewater should be treated to prevent harm to people and animals alike. No outliers being detected in the product from the EGSB or MBR of this study is indicative of the demonstrable robustness of the lab-scale system designed, despite the sporadic changes in PSW quality. The final wastewater output from the pretreatment–EGSB–MBR system met the discharge standards, and this finding can serve to promote such a technology for the treatment of medium-to high-strength wastewater, even in developing countries.

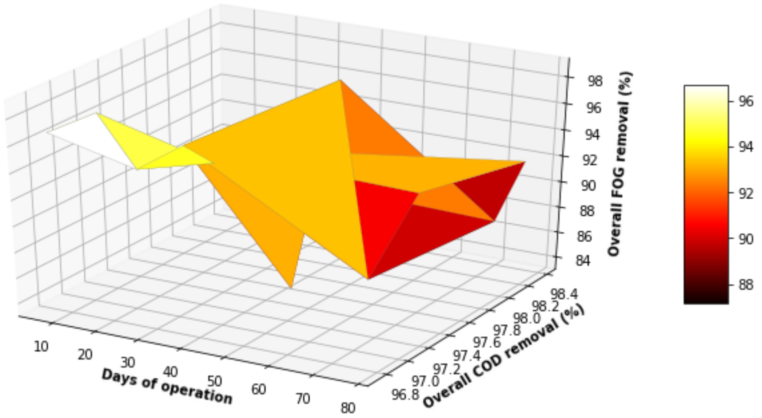



**Figure 3. 21**: 3D plot of the overall performance (COD VS FOG).

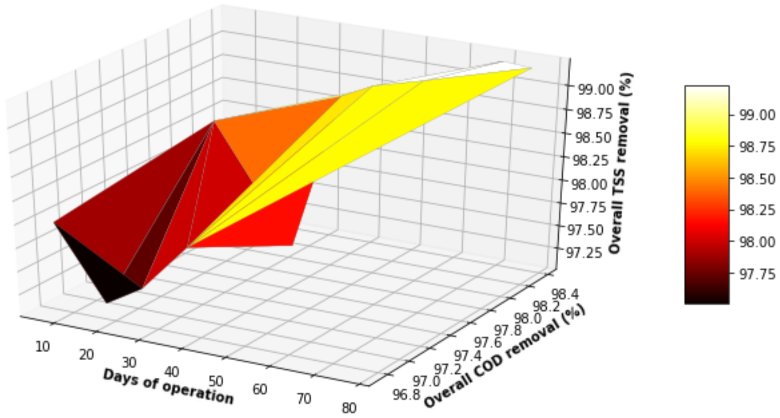



**Figure 3. 22**: 3D plot of the overall performance (COD VS TSS).

**Table 3. 1**: Results obtained from the MBR final effluent compared to standards.

| Parameters | Units | MBR outlet | CoCT by-laws | DWA (2010) | SANS 241;2015 |
|---|---|---|---|---|---|
| pH | n/a | 7.7 | 5.5-9.5 | 5.5-9.5 | 5.5-9.5 |
| Temperature | °C | 22 | 0≤40 | | |
| Conductivity | µs/cm | 350 | ≤500 | ≤200 | ≤170 |
| TDS | ppm | 1000 | 4000 | | |
| tCOD | mg/L | 110 | ≤5000 | ≤5000 | 1000-2400 |
| TSS | mg/L | 8 | 1000 | | |
| FOG | mg/L | 27 | 400 | | |

### 3.4.5. MBR Final Effluent Quality Compared to the Wastewater Discharge Standards

Table 4.1 provides a summary of the results obtained from the MBR outlet compared to wastewater discharge standards from several regulatory bodies, i.e., CoCT, Department of Water Affairs (DWA) 2010, and South African National Standards (SANS) 241:2015 for drinking water. It can be observed that parameters from the MBR outlet such as pH, temperature, conductivity, TDS, tCOD, TSS, and FOG were within the CoCT discharge standards, with only the conductivity not being within the DWA (2010) standards; a possible solution for conductivity might be to recommend continuous monitoring and maintenance of the poultry slaughterhouse wastewater pilot plant.

Furthermore, Table 4.2 lists the performance of similar technologies used in previous studies for the biological treatment of closely related wastewater, from which it was observed that the performance attained in this study was consistent with that observed using these technologies, although the operational conditions were not similar to those reported in previous studies. This is justified by overall peak COD, TSS, and FOG removal percentages above 98%, which is commendable given the fluctuations of the PSW fed to the system and the short period of acclimation used for the pretreatment–EGSB–MBR system.

**Table 3. 2**: Performance reached in similar wastewater treatment studies.

| References | Technology used | Type of Wastewater | Results |
|---|---|---|---|
| (Williams, 2017) | EGSB | PSW | 69% tCOD removal; 98% TSS removal; 92% FOG removal |
| (Williams, 2017) | Ultrafiltration membrane bioreactor (UFMBR) | PSW | 47% TSS removal; 62% tCOD removal |
| (Williams, 2017) | EGSB-UFMBR | PSW | 92% tCOD removal; 99% TSS removal |
| (Basitere et al., 2016) | EGSB | PSW | 65% total COD removal |
| (L.A. Núñez & Martínez, 1999) | EGSB | slaughterhouse wastewater | 54-80% COD removal |
| (Fuchs et al., 2003) | MBR | wastewater with high organic content | 97% COD removal |

| | | | |
|---|---|---|---|
| (Chu et al., 2005) | Hollow fibre membrane filtration-EGSB | Domestic wastewater | 85-96% COD removal |
| (Sheldon & Erdogan, 2016) | EGSB-MBR | Soft drink industry wastewater | 95% total COD removal |
| (Zhang et al., 2008) | EGSB | palm oil mill effluent | 91% tCOD removal |

**3.5. Summary**

A pretreatment–EGSB–MBR system was used to reduce the concentration of contaminants from a PSW. The pretreatment stage reached a peak performance of 50% for TSS removal, 80% for COD removal, and 82% for FOG removal. The EGSB also performed adequately with a peak removal percentage of 90% for TSS, >70% for COD, and >90% for FOG. Further removal was also observed using the MBR with the removal performance being >95% for both TSS and COD and 80% for FOG. These results culminated in a product with COD, TSS, and FOG concentrations being below the CoCT discharge standards. Moreover, the combination of a pretreatment unit with an EGSB and MBR demonstrated a robustness suitable for PSW treatment even with variations in OLR, highlighting the suitability of such a system for medium- to high-strength wastewater treatment for the poultry industry, which can be operated at low cost and with low energy requirements. It is recommended that a techno-economic analysis of the lab-scale design be undertaken to assess the feasibility of applying such a system on a larger scale in arid regions.

**References**


Apha. 2005. Standard Methods for the Examination of Water and Wastewater. twentieth. Washington, DC, USA: American Public Health Association; AmericanWaterWorks Association; Water Environment Federation.

Avula, R.Y., Nelson, H.M. and Singh, R.K., 2009. Recycling of poultry process wastewater by ultrafiltration. *Innovative Food Science & Emerging Technologies*, 10(1), pp.1-8.

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

Bustillo-Lecompte, C. and Mehrvar, M., 2017. Slaughterhouse wastewater: treatment, management and resource recovery. Physico-chemical wastewater treatment and resource recovery, pp.153-174.

Chu, L.B., Yang, F.L. & Zhang, X.W. 2005. Anaerobic treatment of domestic wastewater in a membrane-coupled expended granular sludge bed (EGSB) reactor under moderate to low temperature. *Process Biochemistry*, 40(3–4): pp.1063–1070.

Cruz-Salomón, A., Ríos-Valdovinos, E., Pola-Albores, F., Lagunas-Rivera, S., Meza-Gordillo, R., Ruíz-Valdiviezo, V.M. and Cruz-Salomón, K.C., 2019. Expanded granular sludge bed bioreactor in wastewater treatment. *Global Journal of Environmental Science and Management*, *5*(1), pp.119-138.

Ergofito. 2019. Poultry Farming, in Cape Town: 4. https://www.ergofito.co.za/application/Grease-Fats-Overview 30 April 2021.

Fuchs, W., Binder, H., Mavrias, G. and Braun, R., 2003. Anaerobic treatment of wastewater with high organic content using a stirred tank reactor coupled with a membrane filtration unit. *Water Research*, *37*(4), pp.902-908.

Gerardi, M.H., 2003. *The microbiology of anaerobic digesters*. John Wiley & Sons.

Haandel, A.C. van & Lubbe, J.G.M. van der. 2012. *Handbook of Biological Wastewater Treatment: Design and Optimisation of Activated Sludge Systems*. 2nd ed. London, UK: IWA Publishing.

Kasiri, S., Mah, F., Zhang, C., Haveroen, M., Ellsworth, S. and Ulrich, A., 2012. Anaerobic processes. *Water Environment Research*, *84*(10), pp.1217-1285.

Kaskote, E., Rinquest, Z., Williams, Y. and Njoya, M., 2019. Performance and Statistical Comparison of the Expanded and Static Granular Sludge Bed Reactors Treating Poultry Slaughterhouse Wastewater.

L.A. Núñez and Martinez, B., 1999. Anaerobic treatment of slaughterhouse wastewater in an expanded granular sludge bed (EGSB) reactor. *Water Science and Technology*, *40*(8), pp.99-106.

Mpentshu, Y. 2018. *Biosurfactant producing biofilms for the enhancement of nitrification and subsequent aerobic denitrification.* (Master's Thesis, Cape Peninsula University of Technology). Cape Town, South Africa.

Mukandi, M. 2017. *Modelling of a bioflocculant supported dissolved air flotation system for fats oil and grease laden wastewater pretreatment* (Master's Thesis, Cape Peninsula University of Technology). Cape Town, South Africa.

Del Nery, V., Damianovic, M.H.Z. & 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): 83–88.

Njoya, M., 2019. *Anaerobic digestion of high strength wastewater in high rate anaerobic bioreactor systems: case of Poultry Slaughterhouse Wastewater (PSW)* (Ph. D. Thesis, Cape Peninsula University of Technology). Cape Town, South Africa.

Njoya, M., Basitere, M. & Ntwampe, S.K.O. 2019. *High Rate Anaerobic Treatment of Poultry Slaughterhouse Wastewater (PSW). New Horizons in Wastewaters Management.* E. Fosso-Kankeu, ed. New York, NY: Nova Science Publishers, Inc.

Njoya, M., Basitere, M., Ntwampe, S.K.O. & Lim, J.W. 2020. Performance evaluation and kinetic modeling of down-flow high-rate anaerobic bioreactors for poultry slaughterhouse wastewater treatment. *Environmental Science and Pollution Research*: pp.9529–9541.

Rinquest, Z, Basitere, M., Ngongang, M.M., Njoya, M. & Ntwampe, S.K.O. 2019. Optimization of the COD Removal Efficiency for a Static Granular Bed Reactor Treating Poultry Slaughterhouse Wastewater.

Rinquest, Z., Basitere, M., Ntwampe, S.K.O. and Njoya, M., 2019. Poultry slaughterhouse wastewater treatment using a static granular bed reactor coupled with single stage nitrification-denitrification and ultrafiltration systems. *Journal of Water Process Engineering*, *29*, pp.100778.

Sheldon, M.S. and Erdogan, I.G., 2016. Multi-stage EGSB/MBR treatment of soft drink industry wastewater. *Chemical Engineering Journal*, *285*, pp.368-377.

Williams, Y. 2017. *Treatment of poultry slaughterhouse wastewater using an expanded granular sludge bed anaerobic digester coupled with anoxic/aerobic hybrid side stream ultrafiltration membrane bioreactor.* (Master's Thesis, Cape Peninsula University of Technology,). Cape Town, South Africa.

Yaakob, M.A., Mohamed, R.M.S.R., Al-Gheethi, A.A.S. and Kassim, A.H.M., 2018. Characteristics of chicken slaughterhouse wastewater. *Chemical Engineering Transactions*, *63*, pp.637-642.

Zhang, Y., Li, Y.A.N., Lina, C.H.I., Xiuhua, L.O.N.G., Zhijian, M.E.I. and Zhang, Z., 2008. Startup and operation of anaerobic EGSB reactor treating palm oil mill effluent. *Journal of Environmental Sciences*, *20*(6), pp.658-663.

# CHAPTER 4

# CONCLUSION AND RECOMMENDATIONS

# Chapter 4: Conclusions and Recommendations

## 4.1. Conclusions

The following conclusions were made regarding the results obtained during this study:

The bench-scale PSW treatment plant consisting of a pre-treatment stage for reduction of FOG, an expanded granular sludge bed reactor (EGSB) for removal of organic matter and a membrane bioreactor (MBR) for further reducing residual organic matter and suspended solids was used to reduce pollutants from the PSW. The pretreatment stage which was used as a primary treatment removed 50% for TSS, 80% for COD and 82% for FOG. The EGSB which was used as a secondary treatment removed 90% for TSS, >70% for COD and >90% for FOG. The MBR which was the tertiary and final treatment further removed contaminants >95% for both TSS and COD and 80% for FOG. The overall system consisting of pretreatment stage-EGSB-MBR removed 97% for both TSS and COD and 97.5% for FOG. These results culminated in a product with COD, TSS, and FOG concentrations being below the CoCT discharge standards. Also, the combination of a pretreatment stage with an EGSB and MBR exhibited a robustness appropriate for PSW treatment even with varieties in OLR, highlighting the appropriateness of such a system for medium- to high-strength wastewater treatment for poultry industries globally, and especially in South Africa.

## 4.2. Recommendations

The following recommendations are made for future studies:

- Implementing a UV system as a post-treatment stage after the MBR for disinfection of the treated water to meet City of Cape Town drinking water standards.
- Focusing on the economic aspects of the PSW pilot plant as future research.
- Looking into the production of biogas from AD with the new design implemented during this study and the methods associated with its commercialization.
- A bacterial analysis should be done to know what kind of microbes are into the Ecoflush and what will be the impact in the treatment of PSW.
- A study for optimization on the treatment of the entire system pre-treatment-EGSB-MBR should be performed.
- Further research should be done on the performance of SND in terms of total nitrogen and UF submerged membrane in terms of residual organic matter on this PSW pilot plant.

- A project should be conducted on the fouling effects, process modelling and kinetics of the UF submerged membrane.
- A study on the mathematical modelling of the PSW pilot plant should be done.
- The effects of the fluctuation of OLR and HRT on the performance of the EGSB should be studied.
- The reduction/or removal of nutrients (phosphorous, sulphates and proteins) may be the focus of future PSW pilot plant study.

# REFERENCES

## References

Abdel Kader, A.M. 2015. a Review of Membrane Bioreactor (Mbr) Technology and Their Applications in the Wastewater Treatment Systems. *Desalination and Water Treatment*, 32(3): 111–119.

Apha. 2005. Standard Methods for the Examination of Water and Wastewater. twentieth. Washington, DC, USA: American Public Health Association; AmericanWaterWorks Association;Water Environment Federation.

Appels, L., Baeyens, J., Degrève, J. & Dewil, R. 2008. Principles and potential of the anaerobic digestion of waste-activated sludge. *Progress in Energy and Combustion Science*, 34(6): 755–781.

Avula, R.Y., Nelson, H.M. and Singh, R.K., 2009. Recycling of poultry process wastewater by ultrafiltration. *Innovative Food Science & Emerging Technologies*, 10(1), pp.1-8.

Basitere, M., 2017. *Performance evaluation of an up-and down-flow anaerobic reactor for the treatment of poultry slaughterhouse wastewater in South Africa* (Master's Thesis, Cape Peninsula University of Technology). Cape Town, South Africa.

Basitere, M., Njoya, M., Rinquest, Z., Ntwampe, S.K.O. and Sheldon, M.S., 2019. Performance evaluation and kinetic parameter analysis for static granular bed reactor (SGBR) for treating poultry slaughterhouse wastewater at mesophilic condition. *Water Practice and Technology*, 14(2), pp.259-268.

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

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

Bhattacharyya, D. and Singh, K.S., 2009. Understanding the mixing pattern in an anaerobic expanded granular sludge bed reactor: effect of liquid recirculation. *Journal of Environmental Engineering*, *136*(6), pp.576-584.

Bustillo-Lecompte, C. and Mehrvar, M., 2017. Slaughterhouse wastewater: treatment, management and resource recovery. Physico-chemical wastewater treatment and resource recovery, pp.153-174.

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(4), pp.175-186.

Chávez P., C., Castillo L., R., Dendooven, L. & Escamilla-Silva, E.M. 2005. Dendooven, L. and Escamilla-Silva, E.M., 2005. Poultry slaughter wastewater treatment with an up-flow anaerobic sludge blanket (UASB) reactor. *Bioresource technology*, *96*(15), pp.1730-1736.

Chu, L.B., Yang, F.L. & Zhang, X.W. 2005. Anaerobic treatment of domestic wastewater in a membrane-coupled expended granular sludge bed (EGSB) reactor under moderate to low temperature. *Process Biochemistry*, 40(3–4): pp.1063–1070.

City of Cape Town. 2018. Water amendement by-law, 2018. , (May): 23.

Cruz-Salomón, A., Ríos-Valdovinos, E., Pola-Albores, F., Lagunas-Rivera, S., Meza-Gordillo, R., Ruíz-Valdiviezo, V.M. and Cruz-Salomón, K.C., 2019. Expanded granular sludge bed bioreactor in wastewater treatment. *Global Journal of Environmental Science and Management*, *5*(1), pp.119-138.

Dlangamandla, C., 2016. *Bioflocculant dissolved air flotation system for the reduction of suspended solids-lipids-Proteinaceous matter from poultry slaughterhouse wastewater* (Master's Thesis, Cape Peninsula University of Technology). Cape Town, South Africa.

EPA. 1999. Standard Methods for the Examination of Water and Wastewater. , (1): 1–13.

Ergofito. 2019. Poultry Farming, in Cape Town. : 4. https://www.ergofito.co.za/application/Grease-Fats-Overview (30 April 2021).

Evren, M., Ozgun, H., Kaan, R. & Ozturk, I. 2012. Anaerobic Treatment of Industrial Effluents: An Overview of Applications. *Waste Water - Treatment and Reutilization*.

Fuchs, W., Binder, H., Mavrias, G. and Braun, R., 2003. Anaerobic treatment of wastewater with high organic content using a stirred tank reactor coupled with a membrane filtration unit. *Water Research*, *37*(4), pp.902-908.

Fujishima, S., Miyahara, T. and Noike, T., 2000. Effect of moisture content on anaerobic digestion of dewatered sludge: ammonia inhibition to carbohydrate removal and methane production. *Water Science and Technology*, *41*(3), pp.119-127.

Gerardi, M.H., 2003. *The microbiology of anaerobic digesters*. John Wiley & Sons.

Grady, J., Daigger, G.T. & LIM, H. 2011.Biological wastewater treatment. Second edition. New York: Marcel Dekker, Inc.

Gupta, N., Jana, N. and Majumder, C.B., 2008. Submerged membrane bioreactor system for municipal wastewater treatment process: An overview.

Haandel;, A.C. van & Lubbe, J.G.M. van der. 2012. *Handbook of Biological Wastewater Treatment: Design and Optimisation of Activated Sludge Systems*. 2nd ed. London, UK: IWA Publishing.

Heidlberger, A. & Neugebauer, E. 2015. Membrane Processes - Review.

Heninger, L. 2017. A description of the processes generating wastewater in a poultry plant and a typical pretreatment and full treatment system. *Managing As Mission: Nonprofit Managing for Sustainable Change*: 51–125.

Hydro-Flo Technologies, I. 1990. Poultry Processing Wastewater Treatment System Process Description. : 1–7.

Integral laboratories. 2019. Chemical and microbiological analysis., 22( the south african national accreditation system page): 1-2.

Iorhemen, O.T., Hamza, R.A. and Tay, J.H., 2016. Membrane bioreactor (MBR) technology for wastewater treatment and reclamation: membrane fouling. *Membranes*, *6*(2), p.33.

Jayathilakan, K., Sultana, K., Radhakrishna, K. and Bawa, A.S., 2012. Utilization of byproducts and waste materials from meat, poultry and fish processing industries: a review. *Journal of food science and technology*, *49*(3), pp.278-293.

Kasiri, S., Mah, F., Zhang, C., Haveroen, M., Ellsworth, S. and Ulrich, A., 2012. Anaerobic processes. *Water Environment Research*, *84*(10), pp.1217-1285.

Kaskote, E., Rinquest, Z., Williams, Y. and Njoya, M., 2019. Performance and Statistical Comparison of the Expanded and Static Granular Sludge Bed Reactors Treating Poultry Slaughterhouse Wastewater.

L.A. Núñez and Martinez, B., 1999. Anaerobic treatment of slaughterhouse wastewater in an expanded granular sludge bed (EGSB) reactor. *Water Science and Technology*, *40*(8), pp.99-106.

Laiq Ur Rehman, M., Iqbal, A., Chang, C.C., Li, W. and Ju, M., 2019. Anaerobic digestion. *Water Environment Research*, *91*(10), pp.1253-1271.

Lapointe, B.E., Herren, L.W., Debortoli, D.D. and Vogel, M.A., 2015. Evidence of sewage-driven eutrophication and harmful algal blooms in Florida's Indian River Lagoon. *Harmful Algae*, *43*, pp.82-102.

Liu, H., Zhao, X. and Qu, J., 2010. Electrocoagulation in water treatment. In *Electrochemistry for the Environment* (pp. 245-262). Springer, New York, NY.

Lo, Y.M., Cao, D., Argin-Soysal, S., Wang, J. and Hahm, T.S., 2005. Recovery of protein from poultry processing wastewater using membrane ultrafiltration. *Bioresource Technology*, *96*(6), pp.687-698.

Lohani, S.P. and Havukainen, J., 2018. Anaerobic digestion: factors affecting anaerobic digestion process. In *Waste Bioremediation* (pp. 343-359). Springer, Singapore.

Marchesi, C.M., Paliga, M., Oro, C.E., Dallago, R.M., Zin, G., Di Luccio, M., Oliveira, J.V. and Tres, M.V., 2021. Use of membranes for the treatment and reuse of water from the pre-cooling system of chicken carcasses. *Environmental technology*, *42*(1), pp.126-133.

Van der Marel, P., Zwijnenburg, A., Kemperman, A., Wessling, M., Temmink, H. and van der Meer, W., 2010. Influence of membrane properties on fouling in submerged membrane bioreactors. *Journal of membrane science*, *348*(1-2), pp.66-74.

Meyo, H.B., Njoya, M., Basitere, M., Ntwampe, S.K.O. and Kaskote, E., 2021. Treatment of Poultry Slaughterhouse Wastewater (PSW) Using a Pretreatment Stage, an Expanded Granular Sludge Bed Reactor (EGSB), and a Membrane Bioreactor (MBR). *Membranes*, *11*(5), p.345.

Mittal, G.S., 2006. Treatment of wastewater from abattoirs before land application—a review. *Bioresource technology*, *97*(9), pp.1119-1135.

Mpentshu, Y. 2018. *Biosurfactant producing biofilms for the enhancement of nitrification and subsequent aerobic denitrification.* (Master’s Thesis, Cape Peninsula University of Technology). Cape Town, South Africa.

Mukandi, M. 2017. *Modelling of a bioflocculant supported dissolved air flotation system for fats oil and grease laden wastewater pretreatment* (Master’s Thesis, Cape Peninsula University of Technology). Cape Town, South Africa.

De Nardi, I.R., Del Nery, V., Amorim, A.K.B., Dos Santos, N.G. and Chimenes, F., 2011. Performances of SBR, chemical–DAF and UV disinfection for poultry slaughterhouse wastewater reclamation. *Desalination*, *269*(1-3), pp.184-189.

Del Nery, V., Damianovic, M.H.Z. & 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): 83–88.

Njoya, M., 2019. *Anaerobic digestion of high strength wastewater in high rate anaerobic bioreactor systems: case of Poultry Slaughterhouse Wastewater (PSW)* ( Ph. D. Thesis, Cape Peninsula University of Technology). Cape Town, South Africa.

Njoya, M., Basitere, M. & Ntwampe, S.K.O. 2019. *High Rate Anaerobic Treatment of Poultry Slaughterhouse Wastewater (PSW). New Horizons in Wastewaters Management.* E. Fosso-Kankeu, ed. New York, NY: Nova Science Publishers, Inc.

Njoya, M., Basitere, M., Ntwampe, S.K.O. & Lim, J.W. 2020. Performance evaluation and kinetic modeling of down-flow high-rate anaerobic bioreactors for poultry slaughterhouse wastewater treatment. *Environmental Science and Pollution Research*: pp.9529–9541.

Olowoporoku, O.A., 2016. Assessing environmental sanitation practices in slaughterhouses in Osogbo, Nigeria: Taking the good with the bad. *MAYFEB Journal of Environmental Science*, *1*.

Onsekizoglu, P., 2012. Membrane distillation: principle, advances, limitations and future prospects in food industry. *Distillation-Advances from Modeling to Applications*, *282*.

Pescod, M.B. 1992. *Wastewater treatment and use in agriculture - FAO irrigation and drainage*.

Plumber, H.S., Kiepper, B.H. & Ritz, C.W. 2012. Effects of broiler carcass bleed time and scald temperature on poultry processing wastewater. *Journal of Applied Poultry Research*, 21(2): pp.375–383.

Rabah, F. 2010. Physical , chemical and biological Characteristics of Wastewater.

Rajakumar, R., Meenambal, T., Banu, J.R. & Yeom, I.T. 2011. Treatment of poultry slaughterhouse wastewater in upflow anaerobic filter under low upflow velocity. *International Journal of Environmental Science and Technology*, 8(1): pp.149–158.

Rajakumar, R., Meenambal, T., Saravanan, P.M. & Ananthanarayanan, P. 2012. Treatment of poultry slaughterhouse wastewater in hybrid upflow anaerobic sludge blanket reactor packed with pleated poly vinyl chloride rings. *Bioresource Technology*, 103(1): pp.116–122.

Rinquest, Z, Basitere, M., Ngongang, M.M., Njoya, M. & Ntwampe, S.K.O. 2019. Optimization of the COD Removal Efficiency for a Static Granular Bed Reactor Treating Poultry

Slaughterhouse Wastewater.

Rinquest, Z., Basitere, M., Ntwampe, S.K.O. and Njoya, M., 2019. Poultry slaughterhouse wastewater treatment using a static granular bed reactor coupled with single stage nitrification-denitrification and ultrafiltration systems. *Journal of Water Process Engineering*, *29*, pp.100778.

Rivière, D., Desvignes, V., Pelletier, E., Chaussonnerie, S., Guermazi, S., Weissenbach, J., Li, T., Camacho, P. & Sghir, A. 2009. Towards the definition of a core of microorganisms involved in anaerobic digestion of sludge. *ISME Journal*, 3(6): pp. 700–714.

Salihu, A. and Alam, M.Z., 2016. Pretreatment methods of organic wastes for biogas production. *Journal of Applied Sciences*, *16*(3), pp.124-137.

Sawyerr, N., Trois, C., Workneh, T. & Okudoh, V. 2019. An overview of biogas production: Fundamentals, applications and future research. *International Journal of Energy Economics and Policy*, 9(2): pp. 105–116.

Sheldon, M.S. and Erdogan, I.G., 2016. Multi-stage EGSB/MBR treatment of soft drink industry wastewater. *Chemical Engineering Journal*, *285*, pp.368-377.

South African water act. 1998. National Water Act, Act No 36 of 1998. *Water Resources*, (36): 94.

Tchobanoglous, G., Burton, F.L. and Stensel, H.D., 2003. *Wastewater engineering treatment and reuse* (No. 628.3 T252s). Boston, US: McGraw-Hill Higher Education.

Templeton, M.R. and Butler, D., 2011. *Introduction to wastewater treatment*. Bookboon.

Tetreault, A. 2000. Electrocoagulation Process for Wastewater Treatment.

Wiesmann, U., Choi, I.S. and Dombrowski, E.M., 2007. Biodegradation of special organic compounds. *Fundamentals of Biological Wastewater Treatment. Weinheim, Germany: Wiley-VCH*, pp.p195-222.

Williams, Y. 2017. *Treatment of poultry slaughterhouse wastewater using an expanded granular sludge bed anaerobic digester coupled with anoxic/aerobic hybrid side stream ultrafiltration membrane bioreactor.* (Master's Thesis, Cape Peninsula University of Technology,). Cape Town, South Africa.

Yaakob, M.A., Mohamed, R.M.S.R., Al-Gheethi, A.A.S. and Kassim, A.H.M., 2018. Characteristics of chicken slaughterhouse wastewater. *Chemical Engineering Transactions*, *63*, pp.637-642.

Yordanov, D., 2010. Preliminary study of the efficiency of ultrafiltration treatment of poultry slaughterhouse wastewater. *Bulgarian Journal of Agricultural Science*, *16*(6), pp.700-704.

You, H.S., Huang, C.P., Pan, J.R. and Chang, S.C., 2006. Behavior of membrane scaling during crossflow filtration in the anaerobic MBR system. *Separation science and technology*, *41*(7), pp.1265-1278.

ZDHC Wastewater Guidelines. 2019. ZDHC Wastewater Guidelines. *The Zero Discharge of Hazardous Chemicals Programme*.

Zhang, Y., Li, Y.A.N., Lina, C.H.I., Xiuhua, L.O.N.G., Zhijian, M.E.I. and Zhang, Z., 2008. Startup and operation of anaerobic EGSB reactor treating palm oil mill effluent. *Journal of Environmental Sciences*, *20*(6), pp.658-663.

# APPENDICES

# Appendix A: Supplementary figure

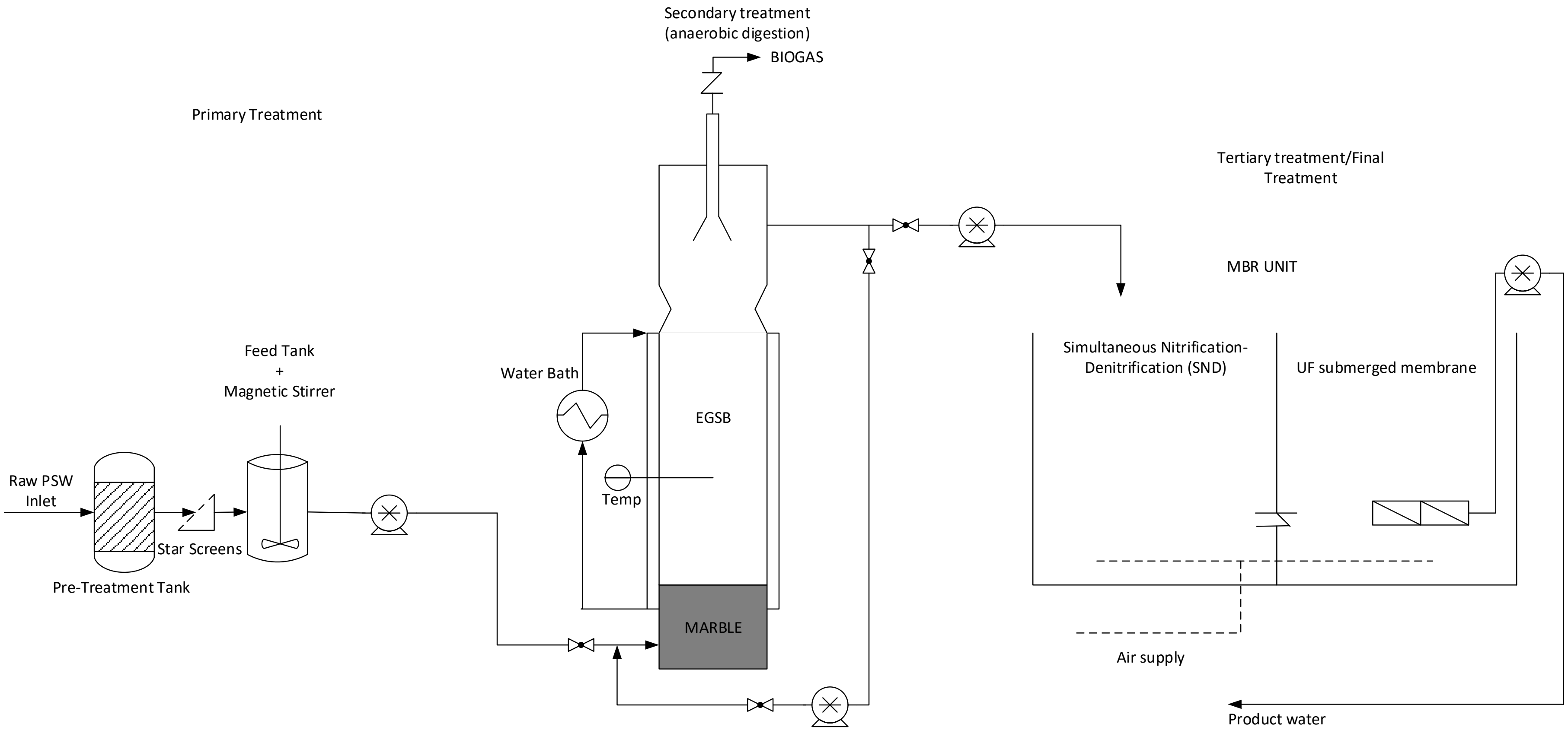



**Figure A. 1**: Bench-scale Poultry Slaughterhouse Wastewater treatment plant.

## Appendix B: External analysis done on PSW.

**Table A. 1**: Summary of the standard test methods done on PSW (EPA, 1999; Integral laboratories, 2019; ZDHC Wastewater Guidelines, 2019).

| Parameters | Technique used | Units | ISO | European Standard | United States |
|---|---|---|---|---|---|
| pH | M6 | / | ISO 10523 | EN ISO 10523 | US EPA 150.1 |
| Temperature | M6 | °C | no standard | no standard | US EPA 17.01 |
| tCOD | M2 | mg/L | ISO 6060** | ISO 6060** | US EPA 410.4,APHA 5220 D** |
| TSS | M8 | mg/L | ISO 11923 | ISO 11923 | US EPA 160.2 |
| FOG | 5520B | mg/L | ISO 9377-2 | EN ISO 9377-2 | US EPA 1664 |
| BOD | M46 | mg/L | ISO 5815-1,-2 (5 days) | EN 1899-1 (5 days) | US EPA 405.1 (5 days) |

## Appendix C: Formulas used for operating parameters.

The following formula was used to determine the HRT of the EGSB reactor:

$$HRT\ (h) = \frac{working\ volume\ of\ reactor\ (m^3)}{flowrate\ of\ influent\ (\frac{m^3}{hr})}$$

$$HRT = \frac{V}{Q} = \frac{2}{0.35} = 5.71\text{hr.}$$

The following formula was used to determine the upflow velocity (Vup) of EGSB:

$$V_{up}(\frac{m}{h}) = \frac{Q\ (\frac{m^3}{h})}{A(m^2)}$$

$$Vup = \frac{h}{HRT} = \frac{0.5914}{5.71} = 0.10\text{ m/hr.}$$

## Appendix D: Tables used to plot graphs.

**Table A. 2**: Pretreatment performance.

| Day count | Date | COD feed | FOG feed | TSS feed | COD product | FOG product | TSS product | COD removal | FOG removal | TSS removal |
|---|---|---|---|---|---|---|---|---|---|---|
| 7 | 17/01/2020 | 4092 | 123 | 1230 | 1667 | 22 | 520 | 59 | 82 | 58 |
| 14 | 24/01/2020 | 4310 | 240 | 340 | 1450 | 104 | 176 | 66 | 57 | 48 |
| 21 | 31/01/2020 | 3210 | 35 | 365 | 881 | 8 | 184 | 73 | 77 | 50 |
| 28 | 01/02/2020 | 3965 | 43 | 198 | 1374 | 11 | 100 | 65 | 74 | 49 |
| 35 | 31/01/2020 | 5900 | 65 | 520 | 3452 | 25 | 348 | 41 | 62 | 33 |
| 42 | 05/02/2020 | 4298 | 72 | 365 | 1988 | 31 | 292 | 54 | 57 | 20 |
| 49 | 11/02/2020 | 4650 | 320 | 1302 | 3525 | 135 | 940 | 24 | 58 | 28 |
| 56 | 18/02/2020 | 5120 | 730 | 1870 | 4092 | 370 | 1173 | 20 | 49 | 37 |
| 63 | 25/02/2020 | 4092 | 340 | 650 | 3096 | 141 | 460 | 24 | 59 | 29 |
| 70 | 02/03/2020 | 13250 | 2870 | 3100 | 4092 | 1478 | 2650 | 69 | 49 | 15 |
| 77 | 09/03/2020 | 4092 | 310 | 645 | 2324 | 79 | 450 | 43 | 75 | 30 |

**Table A. 3**: EGSB performance.

| | | Feed | | | | | | | | | | | Product | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Time | Temp | pH | Cond | TDS | Salinity | tCOD | sCOD | TSS | VSS | Turbidity | HRT | Temp | pH | Cond | TDS | Salinity | tCOD | sCOD | TSS | VSS | Turbidity |
| 1 | 21.35 | 6.54 | 2187.5 | 848 | 580.5 | 2187.5 | 517 | 160 | 318 | 99 | 65 | 20.65 | 8.33 | 3495 | 2470 | 1790 | 2797.5 | 560 | 515 | 3000 | 487.0 |
| 2 | 23.1 | 6.77 | 1134.5 | 811.5 | 550.5 | 2285 | 517 | 160 | 400 | 99 | 65 | 23.45 | 8.49 | 3285 | 2350 | 1690 | 2285 | 563.5 | 150 | 1020 | 391.5 |
| 3 | 23.1 | 6.77 | 1134.5 | 811.5 | 550.5 | 2285 | 517 | 200 | 450 | 99 | 65 | 20.2 | 8.57 | 2855 | 2035 | 1445 | 2285 | 524 | 190 | 575 | 230.0 |
| 4 | 23.1 | 6.77 | 1134.5 | 811.5 | 550.5 | 2285 | 517 | 190 | 995 | 99 | 65 | 22.05 | 8.53 | 2485 | 1765 | 1305 | 2285 | 481.5 | 150 | 550 | 196.0 |
| 7 | 21.65 | 6.54 | 1164.5 | 826.5 | 589.5 | 3512.5 | 510 | 520 | 1500 | 570 | 65 | 21.4 | 8.49 | 2145 | 1515 | 1115 | 1542.5 | 305.5 | 520 | 1500 | 54.6 |

| | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 8 | 22.7 | 6.62 | 1160.5 | 827.5 | 593.5 | 3512.5 | 510 | 520 | 1500 | 801 | 65 | 22.3 | 8.4 | 2050 | 1455 | 1065 | 1542.5 | 305.5 | 520 | 1500 | 113.5 |
| 9 | 22.35 | 6.42 | 1120.5 | 797.5 | 557 | 2922.5 | 302.5 | 240 | 400 | 570.5 | 65 | 23.65 | 8.3 | 2120 | 1500 | 1085 | 1690 | 277 | 50 | 310 | 101.0 |
| 10 | 22.35 | 6.42 | 1120.5 | 797.5 | 557 | 2922.5 | 302.5 | 240 | 400 | 570.5 | 65 | 24.8 | 8.13 | 2055 | 1460 | 1020 | 1690 | 277 | 50 | 310 | 103.5 |
| 11 | 22.85 | 6.50 | 1221 | 866 | 600 | 3162.5 | 302.5 | 300 | 290 | 654.5 | 65 | 19.9 | 8.25 | 2055 | 1475 | 1050 | 1515 | 277 | 300 | 3000 | 70.8 |
| 14 | 21.65 | 6.70 | 1251 | 888.5 | 618.5 | 1985 | 157.5 | 130 | 290 | 259.5 | 65 | 21.25 | 8.31 | 2035 | 1440 | 1020 | 1680 | 177 | 40 | 1590 | 82.7 |
| 15 | 23.45 | 6.39 | 851 | 601.5 | 414 | 1985 | 157.5 | 130 | 290 | 365 | 65 | 23.45 | 8.26 | 1867.5 | 1325 | 942.5 | 1680 | 177 | 40 | 1590 | 24.5 |
| 16 | 24.35 | 6.33 | 831 | 589.5 | 406 | 2727.5 | 276.5 | 330 | 3150 | 603.5 | 65 | 24.45 | 8.19 | 1828 | 1295 | 922 | 1420 | 249 | 170 | 910 | 24.2 |
| 17 | 24.8 | 6.47 | 806.5 | 573 | 392 | 2727.5 | 276.5 | 330 | 3150 | 799 | 65 | 25.55 | 8.07 | 1742 | 1240 | 873.5 | 1420 | 249 | 170 | 910 | 31.4 |
| 18 | 24.8 | 6.47 | 806.5 | 573 | 392 | 1422.5 | 180 | 580 | 1210 | 603.5 | 65 | 24.7 | 7.91 | 1672 | 1185 | 840.5 | 1422.5 | 169 | 30 | 1170 | 15.4 |
| 21 | 24.2 | 6.63 | 827 | 587.5 | 404 | 2532.5 | 165 | 880 | 1280 | 710 | 60 | 23.5 | 7.65 | 1112.5 | 790.5 | 548.5 | 1492.5 | 199 | 50 | 860 | 11.6 |
| 22 | 24.2 | 6.93 | 797.5 | 566.5 | 390.5 | 2532.5 | 165 | 880 | 1280 | 812 | 60 | 23.15 | 7.37 | 1084 | 769 | 535.5 | 1492.5 | 199 | 50 | 860 | 9.0 |
| 23 | 23.65 | 6.64 | 842 | 598 | 413 | 2512.5 | 196.5 | 300 | 1010 | 475.5 | 60 | 23.5 | 6.99 | 856 | 617 | 425.5 | 1422.5 | 218 | 140 | 560 | 18.8 |
| 24 | 23.4 | 6.78 | 851.5 | 604.5 | 417.5 | 2512.5 | 196.5 | 300 | 1010 | 475.5 | 60 | 21.85 | 6.96 | 826 | 589 | 406.5 | 1422.5 | 218 | 140 | 560 | 18.8 |
| 25 | 23.9 | 6.96 | 816.5 | 581.5 | 400.5 | 2537.5 | 215 | 700 | 1210 | 677 | 60 | 23.95 | 7.02 | 822 | 583 | 402 | 1455 | 198.5 | 70 | 1115 | 17.5 |
| 28 | 19.65 | 6.58 | 892 | 634 | 435.5 | 2232.5 | 177.5 | 500 | 1780 | 420.5 | 60 | 20.45 | 6.80 | 784 | 560 | 237.5 | 1495 | 154 | 80 | 1130 | 10.0 |
| 29 | 20.4 | 6.72 | 828.5 | 583.5 | 401.5 | 2232.5 | 177.5 | 500 | 1780 | 473.5 | 60 | 21.55 | 6.74 | 779 | 555 | 381.5 | 1495 | 154 | 80 | 1130 | 37.1 |
| 30 | 21.5 | 6.88 | 823.5 | 585 | 405 | 2467.5 | 138 | 500 | 1740 | 633.5 | 60 | 21.5 | 6.75 | 756 | 553.5 | 381 | 1415 | 127 | 90 | 1170 | 30.5 |
| 31 | 21.5 | 6.91 | 880 | 625 | 426.5 | 2467.5 | 138 | 500 | 1740 | 711 | 60 | 21.5 | 6.66 | 746 | 526 | 357 | 1415 | 127 | 90 | 1170 | 35.2 |
| 32 | 21.35 | 6.94 | 869 | 617 | 421 | 2520 | 164 | 440 | 1760 | 536 | 60 | 21.3 | 6.32 | 728 | 516.5 | 350 | 1392.5 | 155 | 120 | 1440 | 24.2 |
| 35 | 23.1 | 7.24 | 868.5 | 614.5 | 433 | 2727.5 | 128.5 | 805 | 705 | 738 | 60 | 23.3 | 6.50 | 668 | 473 | 329 | 1340 | 89.5 | 45 | 140 | 13.2 |
| 36 | 24.95 | 7.17 | 897 | 641.5 | 464.5 | 2727.5 | 128.5 | 805 | 705 | 790 | 60 | 24.85 | 6.41 | 664 | 473 | 328.5 | 1340 | 89.5 | 45 | 140 | 25.7 |

| | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 37 | 21.05 | 7.00 | 833.5 | 587.5 | 409.5 | 3600 | 180.5 | 60 | 145 | 116 | 60 | 21.25 | 6.42 | 641 | 455 | 315 | 1485 | 130.5 | 10 | 65 | 26.4 |
| 38 | 23.9 | 6.83 | 889 | 632 | 443.5 | 3600 | 180.5 | 60 | 145 | 828.5 | 60 | 23.8 | 6.47 | 649 | 460.5 | 319.5 | 1485 | 130.5 | 10 | 65 | 20.9 |
| 39 | 19.3 | 7.62 | 873.5 | 622.5 | 434.5 | 3812.5 | 198 | 895 | 1010 | 854.5 | 60 | 20.5 | 6.21 | 559 | 396.5 | 273.5 | 1612.5 | 146.5 | 135 | 125 | 44.5 |
| 42 | 21.1 | 6.77 | 908.5 | 645 | 451 | 4360 | 165.5 | 1900 | 1950 | 993.5 | 60 | 20.95 | 6 | 579 | 410.5 | 283.5 | 1607.5 | 118.5 | 110 | 270 | 11.9 |
| 43 | 21.1 | 6.77 | 908.5 | 645 | 451 | 4360 | 165.5 | 1900 | 1950 | 993.5 | 60 | 20.95 | 6 | 579 | 410.5 | 283.5 | 1607.5 | 118.5 | 110 | 270 | 11.9 |
| 44 | 22.1 | 6.87 | 1041 | 739 | 521 | 2215 | 263 | 585 | 650 | 633 | 55 | 21.85 | 6.25 | 524 | 372 | 269.5 | 1585 | 95.5 | 45 | 90 | 158.5 |
| 45 | 22.05 | 6.88 | 1289 | 912.5 | 625.5 | 2215 | 263 | 585 | 650 | 609 | 55 | 22.2 | 6.51 | 561 | 398 | 264.5 | 1585 | 95.5 | 45 | 90 | 23.1 |
| 46 | 21.65 | 7.00 | 1150 | 816.5 | 556 | 2957.5 | 195 | 1000 | 990 | 764 | 55 | 21.65 | 6.79 | 594 | 422.5 | 281 | 1392.5 | 107 | 45 | 280 | 29.2 |
| 49 | 19.9 | 6.75 | 1478.5 | 1050 | 718 | 3760 | 438 | 810 | 1170 | 727 | 55 | 19.8 | 6.72 | 645 | 456.5 | 303 | 1502.5 | 150 | 60 | 250 | 4.3 |
| 50 | 19.9 | 6.75 | 1478.5 | 1050 | 718 | 3760 | 438 | 810 | 1170 | 727 | 55 | 19.8 | 6.72 | 645 | 456.5 | 303 | 1502.5 | 150 | 60 | 250 | 4.3 |
| 51 | 21.75 | 7.13 | 1512 | 1075 | 738.5 | 4027.5 | 573.5 | 745 | 920 | 428.86 | 55 | 21.8 | 7.14 | 851 | 603 | 404.5 | 1762.5 | 173.5 | 175 | 335 | 119.0 |
| 52 | 21.7 | 7.51 | 1499 | 1065 | 742 | 4027.5 | 573.5 | 745 | 920 | 749 | 55 | 21.8 | 7.37 | 892 | 633.5 | 433 | 1762.5 | 173.5 | 175 | 335 | 35.2 |
| 53 | 16.55 | 6.81 | 1585.5 | 1120 | 824 | 3827.5 | 396.5 | 980 | 1230 | 932.5 | 55 | 16.6 | 7.44 | 888 | 632.5 | 451 | 1352.5 | 197 | 160 | 340 | 22.8 |
| 56 | 16.65 | 6.88 | 1425 | 1010 | 736.5 | 4130 | 657.5 | 890 | 1070 | 662 | 55 | 16.75 | 7.42 | 981 | 696 | 498 | 1402.5 | 228 | 80 | 240 | 19.2 |
| 57 | 17.15 | 6.76 | 1473.5 | 1035 | 757 | 4130 | 657.5 | 890 | 1070 | 648.5 | 55 | 17.45 | 7.37 | 1212 | 865.5 | 622 | 1402.5 | 228 | 80 | 240 | 86.2 |
| 58 | 20.85 | 6.87 | 1508 | 1070 | 781.5 | 4700 | 739 | 1070 | 1230 | 554.5 | 55 | 20.5 | 7.28 | 1196 | 848.5 | 613 | 1585 | 208.5 | 20 | 270 | 33.7 |
| 59 | 19.6 | 6.79 | 1572.5 | 1120 | 816 | 4700 | 739 | 1070 | 1230 | 812 | 55 | 19.65 | 7.31 | 1206 | 855.5 | 620 | 1585 | 208.5 | 20 | 270 | 28.5 |
| 60 | 19.45 | 7.01 | 1723 | 1225 | 871.5 | 5837.5 | 389 | 1935 | 2060 | 809 | 55 | 19.45 | 7.50 | 1289 | 916 | 645 | 1760 | 155 | 10 | 660 | 38.2 |
| 63 | 18.7 | 6.86 | 1578 | 1125 | 806.5 | 4240 | 489.5 | 680 | 775 | 821 | 55 | 19.05 | 7.88 | 1317 | 935 | 667.5 | 1335 | 152.5 | 30 | 290 | 4.8 |
| 64 | 19.8 | 6.93 | 1675.5 | 1190 | 859 | 4240 | 489.5 | 680 | 775 | 838 | 55 | 19.85 | 7.70 | 1350 | 958.5 | 685 | 1335 | 152.5 | 30 | 290 | 4.8 |
| 65 | 19.7 | 6.51 | 1778 | 1265 | 926 | 6667.5 | 689 | 2215 | 2440 | 644.5 | 55 | 20.25 | 7.70 | 1287 | 913.5 | 660 | 1392.5 | 170 | 20 | 700 | 4.2 |

| | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 66 | 20.4 | 6.85 | 1520 | 1075 | 785 | 6667.5 | 689 | 2215 | 2440 | 461 | 55 | 20.6 | 7.61 | 1333 | 948 | 687 | 1392.5 | 170 | 20 | 700 | 9.0 |
| 67 | 21.15 | 6.68 | 1524.5 | 1085 | 788 | 4227.5 | 689 | 1755 | 1940 | 742 | 55 | 20.25 | 7.76 | 1311 | 932.5 | 686.5 | 1365 | 213 | 10 | 700 | 17.5 |
| 70 | 18.25 | 6.58 | 1483 | 1060 | 779 | 4057.5 | 895.5 | 810 | 1425 | 778 | 55 | 19.8 | 7.51 | 1391 | 988 | 727 | 1387.5 | 99.5 | 65 | 840 | 11.7 |
| 71 | 18.55 | 6.61 | 1493 | 1060 | 803 | 4057.5 | 895.5 | 810 | 1425 | 746.5 | 60 | 19 | 7.49 | 1376 | 977 | 736.5 | 1387.5 | 99.5 | 65 | 840 | 13.2 |
| 72 | 19.15 | 6.79 | 1528 | 1085 | 819 | 4095 | 659 | 715 | 1525 | 795.5 | 60 | 19.45 | 7.52 | 1362 | 965.5 | 721.5 | 1510 | 113 | 40 | 910 | 15.0 |
| 73 | 19.85 | 6.63 | 1543.5 | 1095 | 835 | 4095 | 659 | 715 | 1525 | 790 | 60 | 20 | 7.58 | 1346 | 954 | 721 | 1510 | 113 | 40 | 910 | 13.5 |
| 74 | 19.6 | 7.42 | 1614 | 1145 | 869 | 4457.5 | 697 | 950 | 1410 | 776 | 60 | 20.15 | 7.65 | 1380 | 981 | 738 | 1460 | 223.5 | 20 | 610 | 13.7 |
| 77 | 19.85 | 6.99 | 1435 | 1020 | 774.5 | 5345 | 353.5 | 520 | 1975 | 932.5 | 60 | 20.15 | 7.74 | 1357 | 963.5 | 731.5 | 1517.5 | 207.5 | 25 | 610 | 9.9 |
| 78 | 20 | 6.88 | 1442.5 | 1025 | 771.5 | 5345 | 353.5 | 520 | 1975 | 932.5 | 60 | 20.15 | 7.51 | 1356 | 963 | 724 | 1517.5 | 207.5 | 25 | 610 | 10.2 |
| 79 | 20 | 7.29 | 1441 | 1025 | 779.5 | 4617.5 | 666.5 | 795 | 1605 | 831.5 | 60 | 20.15 | 7.37 | 1401 | 993.5 | 754 | 1600 | 249 | 290 | 590 | 41.0 |
| 80 | 20 | 7.05 | 1416.5 | 1004.5 | 769 | 4617.5 | 666.5 | 795 | 1605 | 916.5 | 60 | 19.95 | 7.71 | 1293 | 919 | 697.5 | 1600 | 249 | 290 | 590 | 19.7 |
| 81 | 20 | 7.00 | 1444.5 | 1025 | 788 | 4540 | 739.5 | 795 | 1335 | 772 | 60 | 19.8 | 7.59 | 1276 | 909 | 691.5 | 1692.5 | 224 | 20 | 550 | 15.4 |
| 84 | 20.05 | 6.84 | 1665 | 1185 | 829 | 4812.5 | 702.5 | 1415 | 1915 | 780.5 | 60 | 19.9 | 7.37 | 1434 | 1019 | 714.5 | 1502.5 | 240 | 80 | 705 | 6.8 |
| 85 | 20.55 | 6.88 | 1639 | 1165 | 824.5 | 4812.5 | 702.5 | 1415 | 1915 | 478 | 60 | 20.6 | 7.21 | 1450 | 1030 | 723 | 1502.5 | 240 | 80 | 705 | 14.8 |
| 86 | 19.75 | 6.73 | 1710.5 | 1210 | 850 | 3917.5 | 541 | 985 | 1470 | 703 | 60 | 19.75 | 7.22 | 1509 | 1075 | 723 | 1362.5 | 346.5 | 135 | 725 | 14.9 |
| 87 | 20.75 | 6.85 | 1761.5 | 1250 | 877.5 | 3917.5 | 541 | 985 | 1470 | 785 | 60 | 20.75 | 7.18 | 1453 | 1030 | 411.5 | 1362.5 | 346.5 | 135 | 725 | 32.3 |
| 88 | 20.35 | 6.82 | 1791.5 | 1275 | 894 | 6740 | 453 | 1795 | 2320 | 701.5 | 60 | 20.4 | 7.91 | 1482 | 1055 | 717.5 | 1507.5 | 226.5 | 270 | 930 | 112.5 |
| 91 | 18.15 | 6.71 | 1410 | 1410 | 981 | 8747.5 | 421.5 | 2740 | 3155 | 701.5 | 60 | 18.2 | 7.65 | 1654 | 1180 | 734.5 | 1352.5 | 240.5 | 150 | 720 | 8.6 |
| 92 | 19.15 | 6.80 | 1415 | 1415 | 982.5 | 8747.5 | 421.5 | 2740 | 3155 | 582.5 | 60 | 19.2 | 7.48 | 1673 | 1185 | 815.5 | 1352.5 | 240.5 | 150 | 720 | 13.2 |
| 93 | 19.9 | 6.82 | 1535 | 1535 | 1105 | 3945 | 865 | 825 | 1320 | 615.5 | 60 | 19.95 | 7.55 | 1657 | 1180 | 816 | 1265 | 363 | 160 | 1035 | 15.6 |
| 94 | 19.75 | 7.00 | 2175 | 1545 | 1115 | 3945 | 865 | 825 | 1320 | 713 | 60 | 20.7 | 7.68 | 1691 | 1215 | 836.5 | 1265 | 363 | 160 | 1035 | 14.6 |

| | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 95 | 19.65 | 6.82 | 2180 | 1555 | 1125 | 4962.5 | 716 | 955 | 1810 | 765 | 60 | 20.25 | 7.69 | 1791 | 1270 | 868 | 1310 | 271 | 255 | 1115 | 18.6 |
| 98 | 18.15 | 6.18 | 2360 | 1675 | 1215 | 5022.5 | 1049.5 | 1370 | 1810 | 683 | 60 | 17.85 | 7.67 | 1920 | 1365 | 976 | 1242.5 | 336.5 | 170 | 1090 | 12.0 |
| 99 | 19.5 | 6.16 | 2085 | 1475 | 1090 | 5022.5 | 1049.5 | 1370 | 1810 | 656.5 | 60 | 19.45 | 7.67 | 1894 | 1345 | 990.5 | 1242.5 | 336.5 | 170 | 1090 | 39.8 |
| 100 | 19.7 | 6.14 | 2080 | 1475 | 1090 | 4745 | 795 | 1165 | 2120 | 885.5 | 60 | 19.8 | 7.83 | 1921 | 1360 | 997.5 | 690 | 392.5 | 215 | 1255 | 77.2 |
| 101 | 20.35 | 6.38 | 2130 | 1515 | 1110 | 4745 | 795 | 1165 | 2120 | 922 | 60 | 20.9 | 7.83 | 1881 | 1335 | 972.5 | 690 | 392.5 | 215 | 1255 | 81.6 |
| 102 | 21.15 | 6.53 | 2105 | 1495 | 1100 | 6257.5 | 486 | 2090 | 2895 | 896.5 | 60 | 19.85 | 7.76 | 1834 | 1300 | 948 | 812.5 | 497.5 | 135 | 1270 | 66.9 |
| 105 | 20.2 | 6.46 | 2020 | 1435 | 1100 | 3937.5 | 638 | 490 | 1320 | 942.5 | 60 | 20.75 | 7.73 | 1820 | 1290 | 962.5 | 585 | 241 | 60 | 1040 | 19.3 |
| 106 | 18.4 | 6.78 | 2080 | 1475 | 1085 | 3937.5 | 638 | 490 | 1320 | 923.5 | 60 | 20.4 | 7.41 | 1859 | 1320 | 967.5 | 585 | 241 | 60 | 1040 | 28.2 |
| 107 | 19.85 | 6.46 | 2050 | 1455 | 1080 | 6695 | 1021 | 2270 | 3070 | 789 | 60 | 18.4 | 7.66 | 1849 | 1315 | 1141.5 | 855 | 245 | 50 | 870 | 23.9 |
| 108 | 21.4 | 7.07 | 2010 | 1435 | 1065 | 6695 | 1021 | 2270 | 3070 | 617 | 60 | 20.3 | 7.95 | 1830 | 1300 | 961.5 | 855 | 245 | 50 | 870 | 21.1 |
| 109 | 21.4 | 7.30 | 2015 | 1430 | 1065 | 9712.5 | 846 | 4345 | 5055 | 381 | 60 | 21.35 | 8.11 | 1807 | 1285 | 948.5 | 677.5 | 242.5 | 165 | 1260 | 17.6 |
| 112 | 21.8 | 7.30 | 1264.5 | 897.5 | 653.5 | 2372.5 | 837.5 | 980 | 1630 | 468.5 | 60 | 21.85 | 8.00 | 1585 | 1130 | 828.5 | 665 | 208 | 160 | 1120 | 12.0 |
| 113 | 21 | 6.99 | 1233.5 | 876 | 640.5 | 2372.5 | 837.5 | 980 | 1630 | 987 | 60 | 20.9 | 7.85 | 1610 | 1140 | 844.5 | 665 | 208 | 160 | 1120 | 10.8 |
| 114 | 20.95 | 6.86 | 1302.5 | 925 | 675 | 2202.5 | 392.5 | 640 | 1840 | 771 | 55 | 21.2 | 7.69 | 1505 | 1075 | 791.5 | 560 | 190.5 | 160 | 1180 | 4.6 |
| 115 | 21.65 | 6.70 | 1200.5 | 853 | 658.5 | 2202.5 | 392.5 | 640 | 1840 | 981.5 | 55 | 21.5 | 7.65 | 1424 | 1010 | 786 | 560 | 190.5 | 160 | 1180 | 4.7 |
| 116 | 19.4 | 6.73 | 1407 | 1003 | 708.5 | 4152.5 | 386 | 1660 | 2600 | 831.5 | 55 | 20.15 | 7.91 | 1444 | 1030 | 718.5 | 592.5 | 155 | 225 | 1125 | 10.9 |
| 119 | 16.15 | 6.77 | 2350 | 1670 | 900 | 3320 | 389.5 | 505 | 1360 | 557 | 55 | 16.65 | 7.95 | 1628 | 1150 | 812.5 | 550 | 129.5 | 130 | 1255 | 7.1 |
| 120 | 17.15 | 6.92 | 2320 | 2145 | 1000 | 3320 | 389.5 | 505 | 1360 | 610 | 55 | 18.7 | 8.08 | 1909 | 1360 | 789.5 | 550 | 129.5 | 130 | 1255 | 51.7 |
| 121 | 19.4 | 6.87 | 1958.5 | 1480 | 1005 | 4295 | 1204 | 1360 | 2290 | 872 | 55 | 18.7 | 7.92 | 1909 | 1360 | 799 | 715 | 139 | 345 | 1215 | 48.3 |
| 122 | 20.7 | 6.70 | 2340 | 1665 | 1245 | 4295 | 1204 | 1360 | 2290 | 772 | 55 | 20.6 | 7.86 | 2000 | 1420 | 1050 | 715 | 139 | 345 | 1215 | 135.0 |
| 123 | 19.4 | 7.17 | 2275 | 1610 | 1200 | 3840 | 730.5 | 695 | 1530 | 433.5 | 55 | 19.8 | 8.23 | 2050 | 1455 | 1085 | 912.5 | 241 | 390 | 1255 | 87.4 |

| | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 126 | 18.95 | 7.21 | 1772 | 1260 | 1050 | 6705 | 241 | 2320 | 3045 | 999 | 55 | 18.85 | 8.18 | 1901 | 1350 | 1130 | 705 | 210.5 | 365 | 1280 | 25.2 |
| 127 | 16.65 | 6.74 | 1819 | 1270 | 893.5 | 6705 | 241 | 2320 | 3045 | 844 | 55 | 16.5 | 8.17 | 2125 | 1465 | 1050 | 705 | 210.5 | 365 | 1280 | 73.9 |
| 128 | 17.45 | 7.40 | 1730.5 | 1185 | 864 | 3685 | 1388.5 | 885 | 1770 | 722.5 | 55 | 17.85 | 8.20 | 1934 | 1340 | 953.5 | 732.5 | 203.5 | 330 | 1250 | 27.1 |
| 129 | 19.15 | 6.82 | 1946 | 1380 | 1075 | 3685 | 1388.5 | 885 | 1770 | 991.5 | 55 | 18.9 | 7.97 | 2055 | 1190 | 1140 | 732.5 | 203.5 | 330 | 1250 | 14.9 |
| 130 | 18.05 | 6.81 | 1729.5 | 1195 | 817 | 5080 | 1326 | 1865 | 2745 | 970 | 55 | 17.7 | 8.08 | 1978 | 1355 | 1140 | 720 | 235.5 | 195 | 1140 | 25.2 |
| 133 | 19.45 | 6.68 | 1878 | 1335 | 1035 | 6577.5 | 1074.5 | 2200 | 3035 | 921.5 | 55 | 19.5 | 7.93 | 1966 | 1395 | 1085 | 2040 | 174.5 | 360 | 1300 | 25.3 |
| 134 | 18.4 | 6.27 | 1916 | 1360 | 1055 | 6577.5 | 1074.5 | 2200 | 3035 | 940.5 | 55 | 19.4 | 7.94 | 1854 | 1315 | 1020 | 2040 | 174.5 | 360 | 1300 | 66.8 |
| 135 | 19.35 | 6.56 | 1667 | 1185 | 917.5 | 5637.5 | 942 | 2170 | 3045 | 877 | 48 | 19.6 | 8.09 | 1893 | 1345 | 1045 | 1545 | 285 | 320 | 1095 | 47.2 |
| 136 | 20.35 | 6.79 | 1564 | 1110 | 860 | 5637.5 | 942 | 2170 | 3045 | 589.5 | 48 | 20.45 | 8.08 | 1757 | 1255 | 972 | 1545 | 285 | 320 | 1095 | 51.0 |
| 137 | 19.3 | 6.54 | 1536.5 | 1095 | 907 | 9640 | 964.5 | 5165 | 5655 | 824 | 48 | 19.4 | 7.80 | 1689 | 1195 | 1000.5 | 827.5 | 240 | 270 | 1200 | 38.8 |
| 140 | 19.95 | 6.08 | 2015 | 1430 | 912 | 7537.5 | 619 | 3410 | 4325 | 732 | 48 | 20.35 | 7.65 | 2095 | 1485 | 949.5 | 1340 | 188.5 | 130 | 1140 | 13.7 |
| 141 | 20.1 | 5.86 | 2050 | 1460 | 930.5 | 7537.5 | 619 | 3410 | 4325 | 888.5 | 48 | 20.95 | 7.41 | 2020 | 1430 | 911.5 | 1340 | 188.5 | 130 | 1140 | 11.4 |
| 142 | 20.15 | 5.95 | 2165 | 1535 | 982 | 5060 | 1282 | 1005 | 2015 | 224 | 48 | 20.35 | 7.64 | 2080 | 1475 | 941.5 | 1362.5 | 197.5 | 110 | 1200 | 22.4 |
| 143 | 19.65 | 6.15 | 2060 | 1465 | 932.5 | 5060 | 1282 | 1005 | 2015 | 744 | 48 | 19.8 | 7.76 | 2145 | 1525 | 973.5 | 1362.5 | 197.5 | 110 | 1200 | 14.0 |
| 144 | 21 | 6.23 | 2065 | 1470 | 939 | 10657.5 | 667.5 | 4390 | 5225 | 634 | 48 | 21 | 7.64 | 2105 | 1490 | 953.5 | 1350 | 133.5 | 270 | 1275 | 8.4 |
| 147 | 19 | 6.63 | 1558 | 1105 | 864 | 10397.5 | 1153 | 4540 | 5325 | 634 | 48 | 18.6 | 7.68 | 1539 | 1090 | 933 | 1640 | 367 | 295 | 940 | 49.6 |
| 148 | 18.9 | 6.65 | 1252.5 | 890 | 759 | 10397.5 | 1153 | 4540 | 5325 | 907 | 48 | 18.65 | 7.74 | 1645 | 1165 | 1005 | 1640 | 367 | 295 | 940 | 57.5 |
| 149 | 18.7 | 7.11 | 1400 | 989 | 848 | 6427.5 | 959 | 1875 | 2715 | 999.5 | 36 | 19.1 | 7.84 | 1585 | 1120 | 968.5 | 1520 | 161 | 250 | 970 | 65.2 |
| 150 | 19.3 | 6.99 | 1269 | 901 | 771 | 6427.5 | 959 | 1875 | 2715 | 833 | 36 | 19.15 | 8.11 | 1500 | 1070 | 917.5 | 1520 | 161 | 250 | 970 | 47.7 |
| 151 | 19.55 | 6.78 | 1207.5 | 856 | 729.5 | 6387.5 | 809.5 | 1790 | 2690 | 999.5 | 36 | 19.5 | 8.42 | 1442 | 1025 | 877 | 1500 | 234.5 | 265 | 1240 | 61.1 |
| 154 | 19.55 | 6.78 | 1207.5 | 856 | 729.5 | 6387.5 | 809.5 | 1790 | 2690 | 999.5 | 36 | 19.5 | 8.42 | 1442 | 1025 | 877 | 1500 | 234.5 | 265 | 1240 | 61.1 |

| | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 155 | 15.5 | 6.11 | 1393.5 | 990.5 | 816 | 6387.5 | 809.5 | 1790 | 2690 | 346.5 | 36 | 16.35 | 7.54 | 1638 | 1170 | 960.5 | 1500 | 234.5 | 265 | 1240 | 56.7 |
| 156 | 18.1 | 6.00 | 1436.5 | 1020 | 848.5 | 8845 | 1298.5 | 3290 | 4150 | 1000 | 36 | 18.45 | 7.34 | 1505 | 1060 | 883 | 1427.5 | 269.5 | 185 | 1120 | 68.5 |
| 157 | 18.8 | 6.03 | 1462 | 1040 | 862 | 8845 | 1298.5 | 3290 | 4150 | 923 | 36 | 18.75 | 7.36 | 1451 | 1025 | 853 | 1427.5 | 269.5 | 185 | 1120 | 133.0 |
| 158 | 20.9 | 6.21 | 1316 | 934 | 795.5 | 8164 | 956.5 | 380 | 1320 | 475 | 36 | 20.2 | 7.41 | 1403 | 996 | 849.5 | 1712.5 | 317.5 | 375 | 1235 | 133.0 |
| 161 | 20.3 | 6.08 | 1498 | 1060 | 910.5 | 7792.5 | 1065 | 2985 | 3840 | 999.5 | 36 | 20.3 | 7.70 | 1674 | 1190 | 1020 | 1790 | 285 | 320 | 1215 | 65.7 |
| 162 | 19.9 | 6.16 | 1227.5 | 867.5 | 927 | 7792.5 | 1065 | 2985 | 3840 | 641 | 36 | 19.9 | 7.91 | 1175 | 833 | 884.5 | 1790 | 285 | 320 | 1215 | 52.2 |
| 163 | 20.35 | 6.46 | 944 | 671 | 847.5 | 7187.5 | 925 | 1975 | 2795 | 953.5 | 36 | 20.65 | 7.83 | 1143 | 808.5 | 856.5 | 1440 | 179.5 | 435 | 1225 | 35.4 |
| 164 | 18.9 | 6.18 | 1052 | 771 | 856 | 7187.5 | 925 | 1975 | 2795 | 1847 | 36 | 18.9 | 7.50 | 1121 | 770.5 | 870 | 1440 | 179.5 | 435 | 1225 | 63.1 |
| 165 | 19.3 | 6.09 | 1140 | 805 | 931.5 | 7575 | 1349.5 | 2585 | 3525 | 1150 | 36 | 19.3 | 7.80 | 1137 | 807 | 884.5 | 1404 | 104 | 190 | 1135 | 106.5 |
| 168 | 20 | 6.69 | 1448 | 1030 | 871 | 11067.5 | 842.5 | 3615 | 4380 | 915 | 36 | 20.1 | 8.27 | 1410 | 1000.5 | 845.5 | 1542.5 | 113.5 | 230 | 1280 | 41.1 |
| 169 | 19.25 | 6.31 | 1388.5 | 970.5 | 817.5 | 11067.5 | 842.5 | 3615 | 4380 | 324.5 | 36 | 19.05 | 7.86 | 1469 | 1040 | 883.5 | 1542.5 | 113.5 | 230 | 1280 | 43.2 |
| 170 | 19.05 | 6.39 | 1424 | 1010 | 855 | 6842.5 | 925 | 1730 | 2715 | 1664 | 36 | 19.1 | 7.75 | 1500 | 1065 | 903.5 | 1450 | 92.5 | 275 | 1210 | 44.3 |
| 171 | 18.9 | 6.53 | 1446 | 1025 | 869.5 | 6842.5 | 925 | 1730 | 2715 | 1757 | 36 | 19.1 | 7.92 | 1490 | 1060 | 895 | 1450 | 92.5 | 275 | 1210 | 27.6 |
| 172 | 20.65 | 6.24 | 1493.5 | 1060 | 901.5 | 9467.5 | 842.5 | 3435 | 2715 | 809 | 36 | 20.95 | 7.89 | 1508 | 1070 | 910 | 1315 | 112 | 330 | 1200 | 24.8 |
| 175 | 17.4 | 6.41 | 1415 | 1005 | 848.5 | 4837.5 | 842.5 | 940 | 2715 | 661.5 | 36 | 17.4 | 8.03 | 1618 | 1145 | 971 | 1415 | 112 | 420 | 1200 | 23.2 |

**Table A. 4:** MBR performance.

| | | Feed | | | Product | | | Removal | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Day count | Date | COD | FOG | TSS | COD | FOG | TSS | COD | FOG | TSS | OLR |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 7 | 17/01/2020 | 1223 | 16 | 476 | 132 | 4 | 13 | 89 | 75 | 97 | 7 |
| 14 | 24/01/2020 | 809 | 26 | 80 | 132 | 5 | 10 | 84 | 81 | 88 | 5 |
| 21 | 31/01/2020 | 395 | 4 | 14 | 100 | 3 | 5 | 75 | 25 | 64 | 2 |
| 28 | 01/02/2020 | 961 | 5 | 13 | 129 | 2 | 5 | 87 | 60 | 62 | 6 |
| 35 | 31/01/2020 | 1174 | 5 | 150 | 134 | 2 | 11 | 89 | 60 | 93 | 7 |
| 42 | 05/02/2020 | 1176 | 17 | 126 | 105 | 12 | 9 | 91 | 29 | 93 | 7 |
| 49 | 11/02/2020 | 1556 | 5 | 78 | 98 | 3 | 6 | 94 | 40 | 92 | 9 |
| 56 | 18/02/2020 | 2602 | 129 | 450 | 98 | 38 | 5 | 96 | 71 | 99 | 15 |
| 63 | 25/02/2020 | 2438 | 84 | 328 | 86 | 32 | 5 | 96 | 62 | 98 | 15 |
| 70 | 02/03/2020 | 1809 | 86 | 308 | 70 | 32 | 5 | 96 | 63 | 98 | 11 |
| 77 | 09/03/2020 | 1858 | 71 | 350 | 68 | 25 | 5 | 96 | 65 | 99 | 11 |

**Table A. 5**: Overall system performance.

| Day count | Date | COD feed | FOG feed | TSS feed | COD product | FOG product | TSS product | COD removal | FOG removal | TSS removal |
|---|---|---|---|---|---|---|---|---|---|---|
| 7 | 17/01/2020 | 4092 | 123 | 1230 | 132 | 4 | 13 | 97 | 97 | 99 |
| 14 | 24/01/2020 | 4310 | 240 | 340 | 132 | 5 | 10 | 97 | 98 | 97 |
| 21 | 31/01/2020 | 3210 | 35 | 365 | 100 | 3 | 5 | 97 | 91 | 99 |
| 28 | 01/02/2020 | 3965 | 43 | 198 | 129 | 2 | 5 | 97 | 95 | 97 |
| 35 | 31/01/2020 | 5900 | 65 | 520 | 134 | 2 | 11 | 98 | 97 | 98 |
| 42 | 05/02/2020 | 4298 | 72 | 365 | 105 | 12 | 9 | 98 | 83 | 98 |
| 49 | 11/02/2020 | 4650 | 320 | 1302 | 98 | 3 | 6 | 98 | 99 | 100 |
| 56 | 18/02/2020 | 5120 | 730 | 1870 | 98 | 38 | 5 | 98 | 95 | 100 |
| 63 | 25/02/2020 | 4092 | 340 | 650 | 86 | 32 | 5 | 98 | 91 | 99 |
| 70 | 02/03/2020 | 13250 | 2870 | 3100 | 70 | 32 | 5 | 99 | 99 | 100 |
| 77 | 09/03/2020 | 4092 | 310 | 645 | 68 | 25 | 5 | 98 | 92 | 99 |