Cape Peninsula
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ASSESSMENT OF AN INTEGRATED AND SUSTAINABLE MULTI-STAGE SYSTEM FOR THE TREATMENT OF POULTRY SLAUGHTERHOUSE WASTEWATER

By

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DECLARATION

I, **Phumeza Akhona Dyosile**, declare that the contents of this thesis/dissertation represent my own unaided work and that the thesis/dissertation 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.

Signed: P.A.Dyosile Date: 12/09/2021

ABSTRACT

The poultry industry has become a major contributor to the South African agricultural industry due to the growing affordable poultry product demand compared to other animal protein. However, the water requirements for bird slaughtering and the product preparation processes including cleaning, are extensive. Operating abattoirs is governed by the South African Meat Safety Act no. 40 of 2000 and the Abattoir Hygiene Act no. 121 of 1992, both for high and low producers (quantified by the number of birds slaughtered per day). These acts clearly dictate that the provision of clean and safe consumer products is of importance. To achieve this, bird processing requires at least >15 litres of high pressured, filtered and chlorinated water per bird. A typical high-volume abattoir that slaughters over ten thousand birds per day can produce more than one hundred and fifty thousand litres of poultry slaughterhouse wastewater (PSW) that contains a high concentration of organics, nutrients, solids, fat, oil and grease (FOG) and pathogenic microorganisms. The PSW also contains blood, faecal matter, and traces of urine, skin trimmings, feathers and cleaning products. If such untreated PSW is released to the environment, it will be detrimental to the environment, and can cause challenges for municipal sewer systems. For developing countries, the harmful impact includes eutrophication due to nutrient release, stimulating algae growth, and can cause deoxygenation of receiving surface water as a result of organic loading.

The Greendrop report publicised South Africa's (SA's) water challenges in a report that announced inoperative treatment plants, water lost through poor infrastructure and the release of untreated wastewater into river streams. Thus, highlighting the country's inability to cope with the additional wastewater treatment requirements. To counter these challenges, there are numerous treatment technologies used for the treatment of PSW. The introduction of High-Rate Anaerobic Digesters (HRADs) has not only shown significant contaminant reduction but has displayed an economical benefit of biogas production. These systems, i.e. anaerobic digesters, have been touted as better than aerobic digesters which requires a large volume of dissolved oxygen thus making it an expensive treatment method. Therefore, this study explored the use of anaerobic digesters for the treatment of high-strength, lipid rich PSW using a down-flow expanded granular bed reactor (DEGBR) due to its anaerobic functionality, cost efficiency, high organic removal rate, ability to produce effluent that has minimal suspended solids, an additional recycle stream, which expands the sludge bed, and reduce clogging. Additionally, due to the established limitations in some anaerobic digester (AD) reactor performance studies, this research included a pre-treatment unit with delipidating abilities, i.e. Fat, Oils and grease (FOG) hydrolysis. Moreover, a membrane bioreactor (MBR) as a tertiary unit for treated water polishing.

Over a period of 112 weeks, a pre-treatment, DEGBR and MBR integrated system was operated on a lab-scale. A qualitative analysis was conducted, focusing on the system's FOG, Total Suspended Solids (TSS) and Chemical Oxygen Demand (COD) removal abilities from the PSW. The eco-dosed pre-treatment had a positive effect on the removal and/reduction for FOG, TSS and COD; albeit, FOG removal exceeded an average of 80%. This had a positive effect of DEGBR performance, which was continuously operated at an organic loading rate (OLR) range of ~18 - ~45 g COD/L.h, achieving a COD, TSS and FOG removal of 87, 93, and 90%, respectively. Furthermore, the system's overall average removal, i.e. as an integrated pre-treat-DEGBR-MBR system, achieved >99% COD, TSS and FOG removal as an intended outcome for the treatment of PSW; thus, meeting and exceeding set limits for such effluent discharge for South Africa, and in particular, the City of Cape Town's standards whereby the PSW was sampled.

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"…With God all things are possible." - Matthew 19:26

I thank the Lord, for blessing me with the strength, the patience and the endurance to make it thus far in my journey. It is not my strength, nor my might but Your spirit, Lord, through and through.

To God be the glory for all that he has done.

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DEDICATION

My August in May;

May you find inspiration in this thesis and strive to outrun me by a mile and a half.

-Love Mom

Camagu kooQadi, ooGcwina, ooMphankomo, ooDeshani. Ndiyabulela

RESEARCH OUTPUTS

This thesis has been published in part in the Department of Higher Education and Training (DHET) accredited article(s) and conference proceeding(s), cited below:

Published Conference Proceedings

I. **Dyosile, P.A.,** Basitere, M. & Ntwampe, S.K.O. 2019. “Advanced Treatment Technologies for Poultry Slaughterhouse Wastewater*. 16th SOUTH AFRICA Int'l Conference on Agricultural, Chemical, Biological & Environmental Sciences (ACBES-19)”.* Nov. 18-19, 2019 Johannesburg (S.A.). Vol 3, pp 319 – 323. ISBN: 978-81-943403-0-0.

Published Extended Abstract and Presentation

II. **Dyosile, P.A.,** Basitere, M. & Ntwampe, S.K.O. 2019. “Poultry Slaughterhouse Wastewater Treatment Using a Down-Flow Expanded Granular Bed Reactor Coupled with Single Stage Nitrification-Denitrification System, Submerged Membrane, and Ultraviolet System”*. 12th Eastern European Young Water Professionals Conference*. 31 March -2 April 2021, Riga, Latvia. First Edition, Pp 126-127. ISBN: 978-9934-22-618-2.

Published Article

III. **Dyosile, P.A.,** Mdladla, C., Mahomet, N., Basitere, M., Ntwampe, S.K.O. & Kaskote, E. 20218. 2021. “Assessment of an Integrated and Sustainable Multistage System for the Treatment of Poultry Slaughterhouse Wastewater”*. Membranes*, 11, 582. https://doi.org/10.3390/membranes11080582.

Current Impact Factor: 4.106

5-year Impact Factor: 4.509

JCR category rank: Q1: Polymer Science | Q2: Engineering

THESIS LAYOUT

This research project was conducted in laboratory 1.27, Department of Chemical Engineering, Cape Peninsula University of Technology, Bellville Campus.

Thesis breakdown:

Chapter One; This chapter briefly entails the background of the study, research questions that are to be answered by the study, the aim and objectives, hypothesis and highlights the related but not included materials or information for the study.

Chapter Two; This chapter contains the literature reviewed of the study covering the various technologies for wastewater treatment since the development of research on the treatment of poultry slaughterhouse wastewater, and also the adopted pre- and tertiary treatment stages/units put in place to further treat the DEGBR effluent. This chapter was published and presented in the *16th SOUTH AFRICA Int'l Conference on Agricultural, Chemical, Biological & Environmental Sciences (ACBES-19)". Nov. 18-19, 2019 Johannesburg (S.A.)*.

Chapter Three; This chapter looks into the research methodology and experimental results. It specifies the operating conditions of the treatment system, Materials and Equipment, Experimental Set-up and Operations, Sampling as well as Data Analysis. Furthermore, this chapter discusses results and observations of the study, challenges faced and improvisations made in order to obtain the presented results.

Chapter Four; Conclusion and recommendations.

References; bibliography consulted for the success of this study.

Appendices; additional data not reported within the body of the thesis.

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LIST OF SYMBOLS

Symbols	**Description**	**Units**
A	Area	m^2
E	Removal Efficiency	%
L	Length	m
ℓ	Litre	ℓ
µ	Micron	-
K	Permeability	m^2
ρ	Density	Kg.m^{-3}
Q	Flowrate	ml.s^{-1}
R	Rand	R
V	Reactor Working Volume	m^3
v/v	Volume/volume	%
Φ	Porosity	-
T	Temperature	˚C
t	Time	s
v	Velocity	m.s^{-1}
W$_w$	Wet Mass	g
W$_D$	Dry Mass	g

CHEMICAL FORMULAE

Chemical Formulae	**Name of Compound**
CH_4	Methane
CO_2	Carbon Dioxide
NH_2OH	Hydroxylamine
NH_3	Ammonia
NH_4^+	Ammonium
NO_2^-	Nitrogen dioxide
NO_3^-	Nitrate
N_2	Nitrogen
N_2O	Nitrous oxide
H^-	Hydroxide
H_2	Hydrogen
H_2O	Water
H_2S	Hydrogen Sulphide
PO_3^{4-}	Ortho-phosphate

ABBREVIATIONS

Abbreviation	Definition
AD	Anaerobic Digestion
AS	Activated Sludge
BOD	Biochemical Oxygen Demand
CCT	City of Cape Town
CIP	Cleaning in Place
COD	Chemical Oxygen Demand
Conc.	Concentration
CPUT	Cape Peninsula University of Technology
CSTR	Continuous Stirred Tank Reactor
D	Day
DEGBR	Down-flow Granular Bed Reactor
DI	Deionized
DO	Dissolved Oxygen
DWA	Department of Water Affairs
EGSB	Expanded Granular Bed Reactor
FOG	Fat, Oil and Grease
g	Grams
GDP	Gross Domestic Product
h	Hours
HACCP	Hazard Analysis and Control Point
HRT	Hydraulic Retention Time
Kg	Kilograms

µF	Microfiltration
MBR	Membrane Bioreactor
OLR	Organic Lording Rate
P	Phosphorus
ppm	Parts per million
PSW	Poultry Slaughterhouse Wastewater
SA	South Africa
SAB	South African Breweries
SANS	South African National Standards
SBR	Sequencing Batch Reactor
SGBR	Static Granular Bed Reactor
TDS	Total Dissolved Solids
TKN	Total Kjeldahl Nitrogen
TN	Total nitrogen
TP	Total Phosphorus
TS	Total Solids
TSS	Total Suspended Solids
UASB	Up-flow Anaerobic Sludge Blanket
UF	Ultra Filtration
UV	Ultraviolet
VFA	Volatile Fatty Acids
VSS	Volatile Suspended Solids
WWTP	Wastewater Treatment Plant

GLOSSARY

Acetogenesis	Further break down of volatile fatty acids, due to their instability, forming acetate, carbon dioxide and hydrogen (Basitere, 2017)
Acidogenesis	The transformation of soluble compounds by the fermentative bacteria resulting in alcohol, and unstable volatile acids (Basitere, 2017)
Activated Sludge	Microbial culture responsible for assimilating most of the organic matter (Benefield & Randall, 1980)
Aerobic Digestion	A process whereby organic matter is activated by oxygen, to harmless products (Benefield & Randall, 1980)
Ammonification	Conversion of organic nitrogen to ammonia during Hydrolysis (Akunna *et al,.* 1994)
Anaerobic	System conditions where in the absence of free oxygen, oxyphobic organisms thrive (Njoya, 2017)
Anaerobic Digestion	A process whereby organic matter is converted, in the absence of oxygen, to harmless products (Benefield & Randall, 1980)
Biodegradation	The breakdown of organic matter through microorganisms (Njoya, 2017)

Biogas	Gas release from degradation of organic matter in the absence of oxygen (Sawyerr *et al*., 2019)
Biological Oxygen Demand	Required oxygen for biodegradation of organic matter in wastewater (Benefield & Randall, 1980)
Chemical Oxygen Demand	Required oxygen for oxidation of organic materials to take place (Benefield & Randall, 1980)
Conductivity	The ability of water to transmit an electric current due to the presence of ions (Wachinski, 2013)
Eco-flush	Naturally occurring bacteria from soil which, when activated by water, break down hydrocarbons (FogX, 2019)
Facultative microbes	Microorganisms that survive both the absence and presence of oxygen (Ritter & McCabe, 2004)
Filtration	Ultrafiltration: Pressure drive separation process with distribution pore size range, ø = 0.001-0.05 µm (Wachinski, 2013)
	Nanofiltration: Pressure drive separation process with distribution pore size range, ø = 5 x 10^{-}4-0.001 µm (Nagy, 2019)

High-rate Anaerobic Bioreactor	Biological wastewater treatment system that can operate at lowered hydraulic retention times (Njoya, 2017)
Hydraulic Retention Time	Time with which wastewater is kept in a reactor for treatment (Rinquest, 2017)
Hydrolysis	The breaking down of organic matter into soluble compounds (Geradi, 2003)
Membranes	A barrier with varying distribution pore sizes designed for water filtration (Wachinski, 2013)
Methanogenesis	The conversion of acetate to methane gas from the presence of CO_2 and acetoclastic methanogens (Basitere, 2017)
Methanogens	Methane producing microorganisms (Burlage *et al.,* 1998)
Nitrosomonas	Bacteria which oxidizes ammonia into nitrite in a metabolic process, known as nitritation (Basitere, 2017)
Nutrients	Nitrogen and phosphorus content available in wastewater (Fraunhofer-Gesellschaft, 2010)
Organic Loading Rate	Feeding rate of organic matter (Williams, 2017)

Organic matter (Oxyphilic)	Water oxygen consuming matter which is contrived of carbohydrates, fats and proteins (Ellis, 2004)
Poultry Slaughterhouse Wastewater	High strength wastewater generated from the poultry slaughtering processes (Rinquest, 2017)
Salinity	Amount of dissolved salts in water (Wachinski, 2013)
Solids	Suspended solids: Settable and non-settable colloids in wastewater that can be filtered by minimum of 0.45 micron fibre (Ellis, 2004) Dissolved solids: Pollutant particles available after filtration (Ellis, 2004)
Turbidity	A measure of water discoloration or cloudiness (Wachinski, 2013)

CHAPTER ONE

INTRODUCTION

CHAPTER ONE

1. INTRODUCTION

1.1. Background

Agriculture, for South Africa (SA), is central to food security and economic growth. Over the past year, the sector contributed over R69 billion to the country's gross domestic product (GDP), with the poultry industry, contributing 20.9% of the total agro-economy and also providing one hundred and ten thousand employment opportunities nationwide [1]. The R40 billion industry slaughters ~19 million chickens a week for meat [2], amounting to each South African consuming 67 kg of meat per year [3]. Overall, the steady growth in the poultry industry has been owed to the increase in poultry products demand, due to products relatively affordable prices compared to other animal protein with a wide range of products being produced from a single bird. This suits individual budgets for all South Africans, as various products such as eggs, chicken feet, heads, polony, smoked sausage/ bologna, from the excess meat debris and offal (Liver, gizzard, heart), thus making the business profitable. In addition, though the high-volume production is beneficial to businesses and the economy, poultry production water requirements and repercussions of generated wastewater, are extensive.

1.1.1. Poultry Slaughterhouse Processes and Water Requirements

In a Broiler, the birds are either kept in a lairage area or immediately hung by their ankles, head down on rails [4], depending on the operational volume of the plant. The rail moves the birds into electrical stunning, where a low voltage current renders them unconscious before their throats are slit and allowed to bleed out [5]. Furthermore, the birds are submerged in hot water to prepare them for feather plucking. After evisceration where the head, feet and viscera are removed, the birds are washed, sent through final processing stages, chilled before being packaged and moved to the market [4]. During all these stages, potable water is used in considerable amounts as illustrated in Figure 1; thus generating a high strength wastewater as poultry slaughter wastewater (PSW) with 30% more protein and pathogenic microorganisms [6]. In Figure 1, a typical percentage breakdown of the water consumption in an abattoir drawn from a study by Molapo [4], is illustrated.

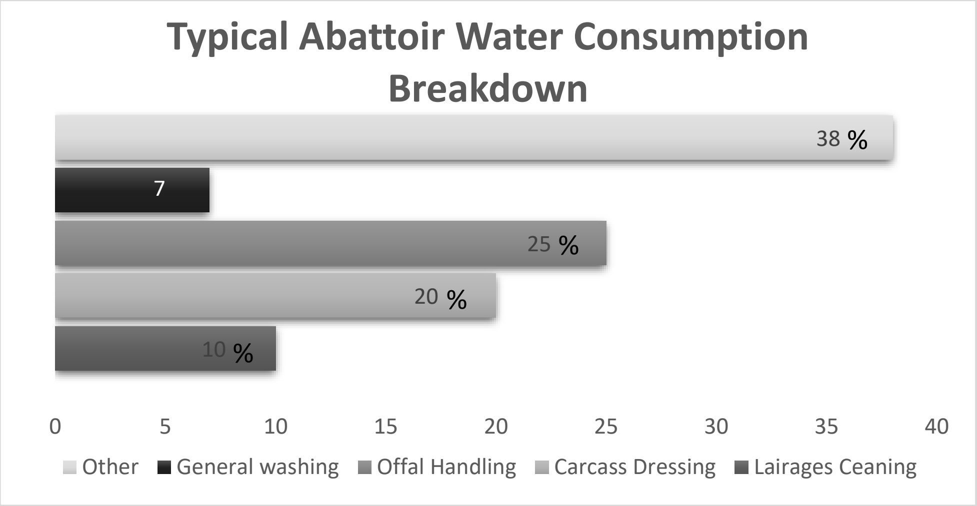

Figure 1: Typical Water Consumption in an Abattoir

Furthermore, Figure 2 offers a detailed water consumption per bird in an abattoir, which is determined by laws dedicated to food safety and environmental impact.

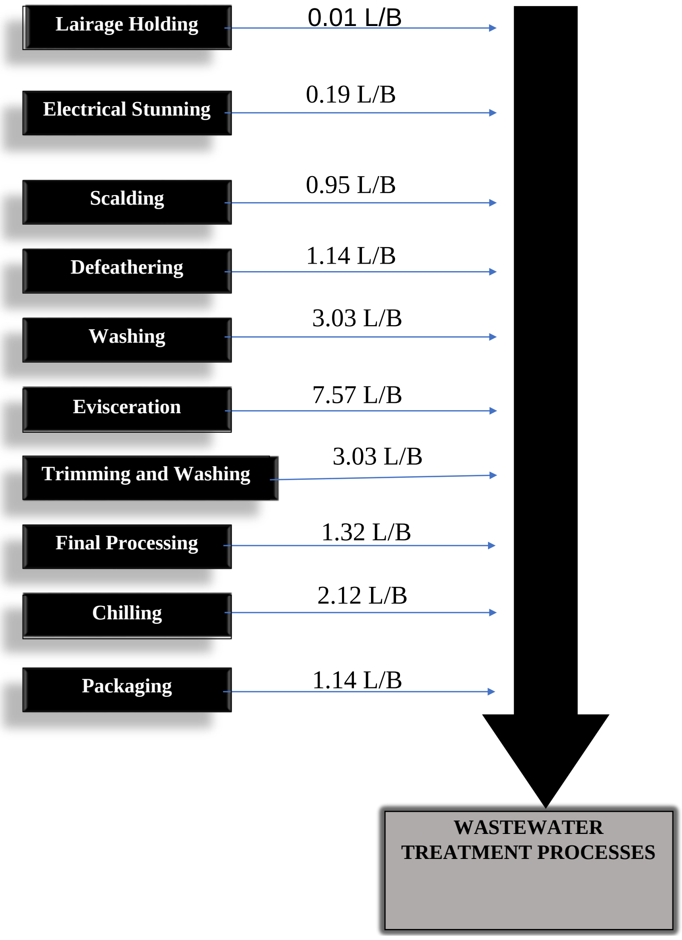

Figure 2: Detailed Process and Generated Wastewater per bird. ***Key: L/B = Litre per Bird

As seen from the breakdown, it is expected that the untreated raw wastewater will be blood-red and contains faecal matter, fat, detergents, meat trimmings and feathers [6]. Moreover, the produced high volumes of PSW are characterised by varying albeit high organic matter, excess nutrients, solids and pathogenic microorganisms from the presence of blood, faecal matter, fats, undigested foods and traces of urine in the water, which are all detrimental to the environment, sewage streams and freshwater bodies [6], [7].

1.1.2. Laws Surrounding Food Safety and Environmental Impact

Among the various legislations put in place for slaughterhouse operations, is the Abattoir Hygiene Act no. 12 of 1992[8], which recommends at least 15 litres of high-pressure potable water be used per bird slaughtered [4], [9]. This act is aimed at ensuring that the environment with which the birds are exposed to is maintained at good standards [4]. Similarly, in support of the abattoir hygiene act, the meat safety Act no. 40 of 2000 [10] aims at providing a final product to consumers that is clean and not harmful. Hence, in a study conducted by [11] a survey to determine the overall water use for broiler processing was conducted. During their hazard analysis and control point (HACCP), it was reported that the average water consumption (affected by bird size and process procedure) was 26 L/bird. It is from these protecting laws lies the impact of high-volume wastewater generation from the extensive slaughtering process.

1.2. Problem Statement

1.2.1. Problem Statement I: Water Scarcity and Environmental Concern

South Africa has been under potable water strain for years and has been reported to be one of the top 30 driest countries in the world [12]. Though the country is already at a disadvantage of getting 40% less rainfall than the annual world average, its challenges also include water lost through leaks, illegal connections [12] and poor treatment plants operating under perilous conditions with inadequate infrastructure, that only treat 60% of the receiving wastewater [13].

With the above stated facts, even though the agricultural industry has made a significant contribution to the economy, the sectors' water usage is colossal exceeding even the domestic water use sector which is characterised by over 58 million citizens' daily water usage – see Table 1 for water usage allocations. Further division, in Figure 3 shows from the 62% water allocation to agriculture, Animal Products utilises 46.5% of the allocated water to cleaning and maintaining the sub sector and its processes.

Table 1: Water Usage by Sector in South Africa [14]

Water User/ Sector	Water Allocation (%)
Agriculture	62
Domestic	27
Industrial	3.5
Afforestation	3
Mining	2.5
Power Generation	2

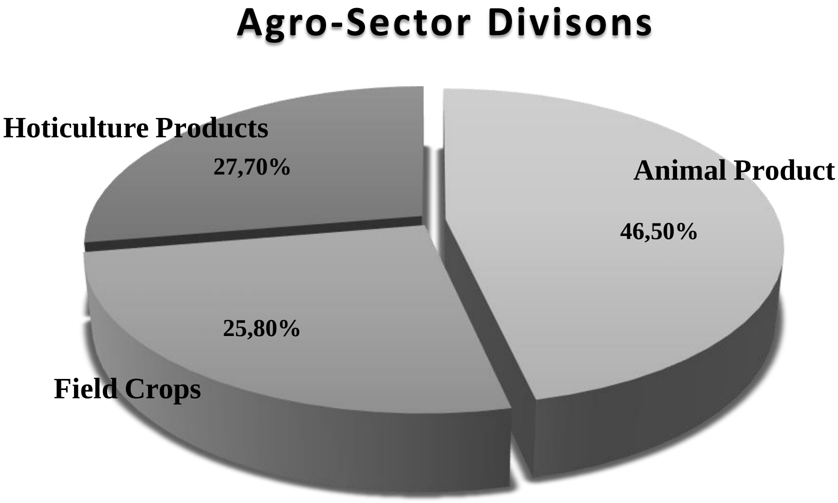

Figure 3: Agro-Sector Economic Contributions

Even with these numbers, safer and healthier products is required. In a study by [15], reported that even with the current water usage of ~40% by poultry abattoirs, most do not comply with the hygiene code of conduct with meat safety being associated with better cleaning including more water usage.

1.2.2. Problem Statement II: Poultry Slaughterhouse Wastewater Characteristics

The PSW collected varies in characteristics depending on the process with which the water was used. Whether it has been for skinning, slaughtering or for cleaning [6]. PSW is characterized as a high-strength wastewater, due to treatment difficulties associated with its high lipid content, which is 35% higher than industrial wastewater protein content, solid and deoxygenating organic load [4], [16]. In recent studies [21], the average PSW characteristics are as summarised in Table 2.

Table 2: PSW Characterization [21].

Parameter	Unit	Range	Average
pH		6.5-8	6.88
Alkalinity	Mg/l	0-489	489
COD	Mg/l	2133-4137	2903
BOD	Mg/l	1100-2750	1667
FOG	Mg/l	131-684	406
TDS	Mg/l	372-936	654
TSS	Mg/l	315-1277	794

Discharge of poultry abattoir waste including the wastewater into the municipal sewer system or land/soil can be classified as pollution of concern with environmental exposure being high due to the high level of organics (i.e. BOD, COD, FOG, TSS) contained therein, which may culminate in eutrophication and deoxygenating of freshwater bodies [17], [18]. The National Water Act no. 36 of year 1998 was set to protect South Africa's water quantity and quality. Furthermore, the Municipal Systems Act no. 32 of year 2000 sets the degree to which the water is to be treated prior to discharge into the sewer or environment which is governed by the water services bylaws set by [4], [19]. In 2013, as part of the water act, Edna Molewa a former South African minister of water and environmental affairs released minimum water requirements applicable for wastewater discharge into water resources, in Gazette no. 19182 [20], as summarised in Table 3.

Table 3: General Limit for Effluent Discharge [20]

Parameter	Unit	General Limit
Faecal Coliforms	Per 100ml	1000
COD	Mg/l	75
pH	Mg/l	5.5-9.5
Ammonia	Mg/l	6
Nitrates	mg/L	15
Chlorine	mg/L	0.25
Suspended Solids	mg/L	25
Soap, Oil and Grease	mg/L	2.5
Electrical conductivity	mS/m	75

1.3. Aim and Objectives

1.3.1. Aim

The aim of this study was to determine the performance of the DEGBR coupled with the MBR including a pre-treatment unit supplemented with a hydrolysis agent for the treatment of poultry slaughterhouse wastewater.

1.3.2. Objectives

The objectives of this study included the following:

- Evaluate the effectiveness of the pre-treatment stage/unit for FOG hydrolysis in particular.
- Evaluate the treatment efficiency of the DEBGR for organics removal, FOG and total suspended solids and perform a similar evaluation for the MBR.
- Determine the performance of the overall set up plant on the reduction of pollutants in the PSW.

1.4. Research Questions

- **-** Will the pre-treatment, high rate anaerobic digester (DEGBR) and membrane bioreactor (MBR) system successfully reduce organic matter, solids and FOG present in PSW?
- **-** Does the DEGBR require additional post-treatment technologies to successfully treat the PSW?
- **-** Does the addition of a pre-treatment unit supplemented with a hydrolysis agent, Eco-Flush, offer value to the overall treatment process?
- **-** Can the overall system provide treatment of the PSW successfully to meet the effluent discharge requirements set by the South African government and specifically the City of Cape Town (CCT)?

1.5. Hypothesis

It was hypothesized that the pre-treatment, down-flow expanded bed reactor coupled membrane bioreactor combined as a single system will treat the high strength poultry slaughterhouse wastewater containing organic matter with solids and achieve significant removal of FOG.

1.6. Significance of the Study

In a world where environmental sustainability has moved to the forefront of every organization’s list, the health and safety of life and the living is crucial. Furthermore, as the world advances, the generation of waste is increasing and posing growing risks to the environment, which calls for more aggressive approaches for waste eradication, which can be achieved by the development of innovative and “green” treatment processes that intensify with the growing intensity of waste generation. Vigorous treatment methods, especially for PSW, which is classified as a high-strength wastewater, prior to discharge, is critical. Thus, the development of the DEGBR as a technology combined with others as filtration using a membrane bioreactor, must be developed and where explored in this study to culminate in a final effluent compliant with set laws for effluent discharge.

1.7. Delineation

This study focuses primarily on the performance of the down-flow expanded bed reactor system, which includes a pre-treatment, an anaerobic digester and a membrane bioreactor. Though the following may be related to the content of this study, it is not included.

- A qualitative and quantitative study on biogas production.
- Operational costs of the research study and pilot plant.
- A study on other industrial available membranes.
- Kinetic modelling
- Optimization of the individual or combined system

All of these parameters can be undertaken in the next phase of the study.

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CAPTER TWO

LITERATURE REVIEW

Dyosile, P.A., Basitere, M. & Ntwampe, S.K.O. 2019. “Advanced Treatment Technologies for Poultry Slaughterhouse Wastewater. 16th SOUTH AFRICA Int'l Conference on Agricultural, Chemical, Biological & Environmental Sciences (ACBES-19)”. Nov. 18-19, 2019 Johannesburg (S.A.). Vol 3, pp 319 – 323. ISBN: 978-81-943403-0-0.

CHAPTER TWO

2. LITERATURE REVIEW: Advanced Treatment Technologies for Poultry Slaughterhouse Wastewater

2.1. Introduction

At 13:58:00, August 26th, year 2019, the world population living in scarce water areas was recorded to be 2 326 604 575 and increasing by the second [1]. At this rate, Guppy and Anderson [2] believed that the global demand is expected to increase with a 50% margin by the year 2030. The growing scarcity of water around the globe is one of the most pressing worldly concerns that may lead to an international conflict among the nations with transboundary aquifers [2]. This certainty and the advancing industrialization and urbanization leaves the whole world in dire straits as of the 71% water covering the earth [3], 97% is saline and of the remaining 3%, 87% is in the form of ice [4], thus leaving only 0.3% potable water which is insufficient for the growing populations and globalization advancements. For this reason and the continued service to population growth and economic boosting industries such as the poultry industry, that requires large volumes of potable water, continuous improvisation for efficient and successful treatment is necessary to treat the intricate wastewater released.

The variation in the composition of poultry slaughterhouse wastewater lies in the various stages of slaughtering. Whether it is slaughtering, defeathering or cleaning of the facilities or the poultry itself, considerable amounts of high strength wastewater is generated from the set laws such as the South African Meat Safety Act no. 40 of 2000 and Abattoir Hygiene Act no. 121 of 1992, that seek to protect the consumer and hold the abattoirs accountable for quality products [5]. Due to this, a study performed by Avula *et al*. [6], showed the average water consumption per bird to be 26.5 L which means high production abattoirs roughly produce over two hundred litres per day.

2.2. Material and System Design

Figure 4 shows the proposed design for treatment of poultry slaughterhouse wastewater.

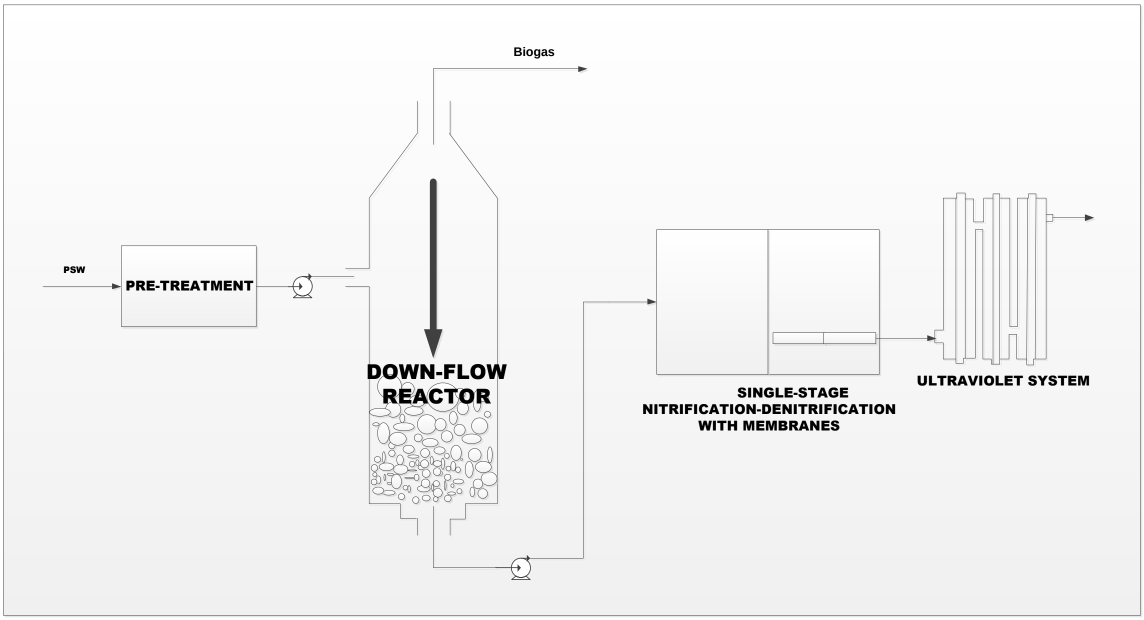

Figure 4: Poultry slaughterhouse treatment system

The treatment system consists of biological treatment prior the anaerobic digestion process for the purposes of hydrolysis. As the PSW contains high content of FOG, this stage plays an important role in lowering the organic load of the feed to the anaerobic digestion process, which will assist in mitigating deficiencies such as sludge washout in up-flow anaerobic digestion and clogging of the underdrain for the down flow configuration reactors. The anaerobic digestion effluent is sent to the single stage nitrification and denitrification (SND) process for nitrogen removal. The product of the SND is the further passed through membranes for solids removal and UV system for pathogen removal.

2.2.1. Poultry Slaughterhouse Characteristics

Though the poultry industry has become the biggest industry in the South African agricultural industry by contributing an approximate amount of 21% and providing over one hundred thousand jobs [7], through the increased demand of products, due to their affordability and their wide range, albeit, the sector generates a high strength wastewater that contains 35% more protein and pathogenic microorganisms due to the presence of blood, fat, oil and grease (FOG) in it [8] and an excessive level of nutrients (NH_4^+, NO^{2-}, PO_4^{3-}), organics (COD, BOD, TOC), solids (TDS,TSS, VSS) and change in physical properties which is detrimental to the environment, municipal sewer systems and poses as a human health hazard [5].

Table 4, shows a representation of typical poultry wastewater characteristics as reported by Basitere [8].

Table 4: Typical Poultry Slaughterhouse Wastewater Characteristics

Parameter	Unit	Range	Average
pH	-	6.5-8	6.88
Alkalinity	mg/l	0-489	489
tCOD	mg/l	2133-10655	6394
sCOD	mg/l	595-1526	974
BOM	mg/l	1100-2750	1667
TKN	mg/l	77-352	211
TP	mg/l	8-27	17
FOG	mg/l	131-684	406
TDS	mg/l	372-936	654
TSS	mg/l	315-1273	794
VSS	mg/l	275-1200	738

2.2.2. General Limit for Effluent Discharge

Over the past decade, the growth of the poultry industry has made it the biggest segment of the Agro-Economy in South Africa [9]. The benefits of the industry include the wide range of products produced from a single bird that works to suit the individual budgets of all South Africans, such as the chicken feet, heads and offal (Liver, gizzard, heart). During the slaughtering and sorting process, the high production rates create a large room for contamination of the meat and poses a risk in environmental hygiene and food safety [5], hence the use of large volumes of high-pressured potable water, to ease the anxious consumers. However, as mentioned above, the generated wastewater contains unwanted constituents which may culminate into eutrophication and deoxygenating of freshwater bodies [8], [10]. Table 5 shows standards for effluent discharge into sewage systems in South Africa. To bridge the gap and meet the general limit of effluent discharge, technology development projects have been done to successfully treat and potentially alleviate current water challenges.

Table 5: general limit for effluent discharge[11]

Parameter	Unit	World Bank Standards	South African Standards
Faecal Coliforms	Per 100ml	-	1000
COD	mg/l	250	75
pH		6-9	5.5-9.5
Ammonia	mg/l	10	6
Nitrates	mg/l	10	15
Chlorine	mg/l	-	0.25
Suspended Solids	mg/l	50	25
Soap, Oil and Grease	mg/l	10	2.5

2.3. Discussion

2.3.1. Poultry slaughterhouse wastewater treatment system trail

There have been numerous treatment technologies used for high strength PSW treatment, both aerobic and anaerobic. The use of aerobic treatment systems (ATD) require a large volume of oxygen to support the biomass, thus making it an expensive treatment method. In comparison to anaerobic digestion, the operating costs are high and the generated sludge requires further dewatering [12].

2.3.2. Anaerobic Digestion

The anaerobic digestion (AD), which uses bacteria as a subjugator for the present organics and has been found as an ideal treatment technology for FOGs and high concentration of particulate removal [12]. In these types of biological reactors, in the absence of oxygen, at mesophilic temperature range (30-40 ^{o}C) and a pH range of 6.5-9 [12], microbial interaction takes place.

It therefore results in a treated effluent with ± 90% treatment efficiency [10], [13] and by-products such as biogas, bio-sludge, ammonium NH_4^+ and phosphate PO_4^{3-} compounds [12].

2.3.3. Microbial Interaction in Anaerobic Digesters

After reactor acclimation and microbial maturation, the PSW introduced into the reactor is broken down into soluble compounds in a process called hydrolysis [8], [14]. Subsequently, these compounds are transformed by the fermentative bacteria resulting in alcohol, and unstable volatile acids in Acidogenesis [12], [15]. Following Acidogenesis, in Acetogenesis, the volatile acids break, due to instability, to form acetate, carbon dioxide and hydrogen [8], [14]. Lastly, in the presence of carbon dioxide, acetoclastic methanogens grow and result in the conversion of acetate to methane in a process called Methanogenesis [8], [14].

2.3.4. High Rate Anaerobic Bioreactors

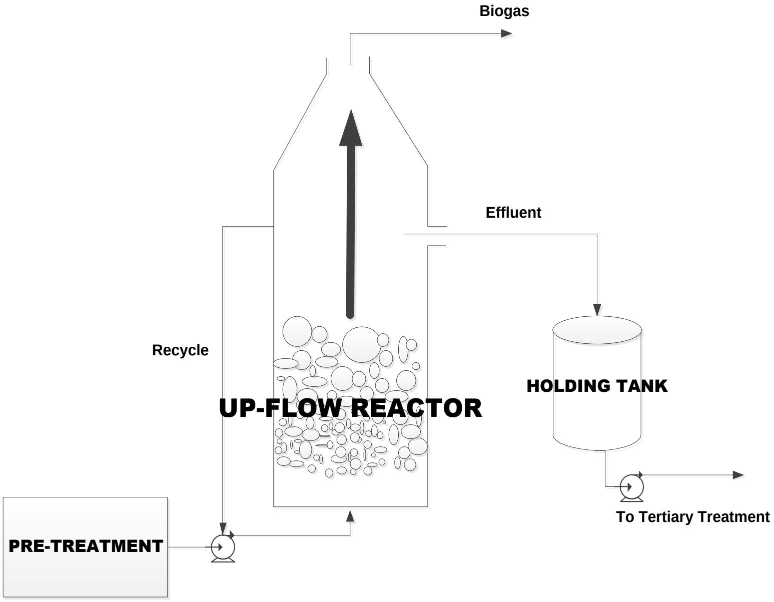

Figure 5: Up-flow configured reactor

The Up-flow Anaerobic Sludge Blanket (UASB) is anaerobic digestion treatment technology, where wastewater enters at the bottom of the reactor and treated through the sludge blanket made of microbial granules [16] after which the Expanded Granular Bed Reactor (EGSB) was developed with the same working principle but an additional recycle stream. These reactors alone have a working efficiency of up to 90% of COD removal and have an ability to withstand high level of organics [16]. However, the success of these reactors relies on the gas-liquid-solid separation system [17], [18]. From studies conducted, Njoya et al. [19] noted that up-flow configured reactors run the risk of sludge washout, resulting in the loss of the microorganisms which further results in increased solid concentration in the effluent and reduced quality of treatment [18].

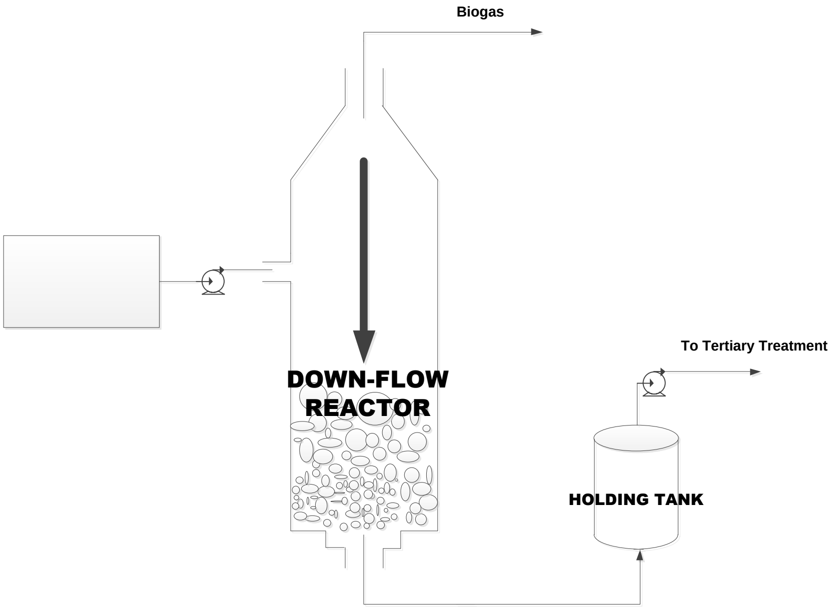

Figure 6: Down-Flow configured reactor

The static granular bed reactor (SGBR), an invention of Ellis from Iowa State University in the year 2000 [20] receives wastewater from the top and the effluent at the bottom of the reactor. From this configuration, the gas-liquid-solid separation stage is unnecessary [18], [19] as the produced biogas bubbles to the top while the gravity acts on the water [18] and present solids and particulates which, overtime, compact on the bed and may lead to reactor clogging [8]. The SGBR has been proven to produce a higher quality effluent than that of the up-flow reactor with COD removal greater than 90% [15].

2.3.5. Available treatment technologies performances

Treatment technologies under the anaerobic digestion include reactors such as Up-flow Anaerobic Sludge Blanket (UASB), Expanded Granular Sludge Bed (EGSB) and Static Granular Bed Reactor (SGBR) each developed from performance evaluations on wastewater treatment.

The UASB, was created in the 1970’s as a substitution to the septic tank [27]. As the name suggests, the reactor has an upward configuration that allows the created biogas to mix with the water and the FOG present in the PSW to attach to the granular sludge, thus resulting in the risk of sludge washout [12]. In study conducted by Saghir and Hajjar [28], for the treatment of poultry slaughterhouse wastewater, the reactor achieved its best COD removal of 83% at hydraulic retention time of 36 hours.

The EGSB is an up-flow velocity derivative of the UASB [27], created in Netherlands in the 1980s to remedy the short coming evident in the UASB [29]. However, along with the UASB, the EGSB's disadvantage includes the additional gas-liquid-solid separation stage, extra energy to overcome gravitational forces [30] and the increased risk of sludge washout, further leading to reduced efficiency [31].

The SGBR, an invention of Ellis [20] is a down flow configured reactor that is an advancement from the up-flow. The configuration requires less steps than the up-flow, less energy, and has a benefit of sludge retention [18], [19]. However, when wastewater contains high total suspended solid and FOG concentration, the reactor is prone to clogging of the underdrain due to the use of pea gravel at the bottom of the reactor. Table 6 shows different efficiencies of individual reactors.

Table 6: COD AND TSS Removal Efficiencies

	COD Removal (%)	**TSS Removal (%)**
UASB	>90	
EGSB	≈67%	≈83%
SGBR	<90	95%

In summary, with regards to Table 3, using information drawn from studies by Rinquest [10], Basitere *et al*. [32] & Tilley *et al*. [16], the SGBR has shown a level of superiority over the other reactors. However, it runs a risk of clogging which can impede the entire system performance. In a study done by Basitere et al., [25] Exploring the treatment of poultry slaughterhouse wastewater using static granular reactor coupled with UF membrane over a 9 week period. The reactor performance of 93% and 95% COD and TSS removal, with the additional of the UF membranes, the system achieved 98% and 99.8% COD and TSS removal respectively. However, Basitere *et al.* [28] noted that compared to a SGBR study conducted in the year 2008 by Evans [18], the reactor performance reached 95.7% suggesting an error in the system which maybe a resulted of a solid build up in the granules or an influence of the organic loading rates. For remedial effect;

a. The addition of a pre-treatment may alleviate clogging and potentially reduce shock loading by reducing the FOG, suspended solids and surface tension in the PSW using the grown facultative microbes as a primary treatment prior to biological treatment. This is also improving the known clogging and fouling of membranes.
b. The addition of a recycle to periodically fluidised the sludge, thus resulting in a hybrid-SGBR may significantly reduce clogging.

However, overall, these high rate anaerobic reactors produce good quality effluents from the high strength poultry wastewater, the advancing requirements for effluent discharge care for produced by-products (NH^{4+}, PO_4^{3-}) as well, listed in the general limit for effluent discharge section, necessitating the need for tertiary treatments to improve the quality and remedy deficiencies not accomplished by the bioreactor. These include nutrient removal by single-stage nitrification-denitrification, particulates and pathogens by membranes.

Part of the disadvantages of anaerobic digestion, is its inability to remove maximal nitrogen. For curation, the single-stage nitrification-denitrification is used. However, prior nitrification and denitrification, ammonification takes place in the anaerobic reactor during hydrolysis where organic nitrogen is converted to ammonia [21]. The two equations 1 and 2 signify the nitrification process which begins in an aerated environment, where the Nitrosomonas bacteria converts ammonia and ammonium to nitrite at high retention times [10]. A study by Rinquest *et al*. [22] showed that increased retention times resulted in an optimum TN removal, that increased TN removal from 33% to 79%.

$$2NH_3 + 7/2O_2 \rightarrow 2NO_2 + 2H_2O + 2H^+ \text{ [14] (1)}$$

This is followed by the conversion of nitrite to nitrate due to the nitrobacteria [10], [14].

$$NO_2 \xrightarrow{\text{Oxygen Environ.}} NO_3^- \text{ (2)}$$

In denitrification, the nitrates are reduced to nitrogen gas [23]. Reaction requirements include; a sufficient carbon source, heterotrophic bacteria and an anoxic environment [10]; [23].

Combined SND reaction: $NH_4^+ \rightarrow NH_2OH \rightarrow N_2O \rightarrow N_2$ [14] (3)

Pochana and Keller [23] proved for a 95% total nitrogen removal. The ratio 5:20 TOD:TKN for denitrification, dissolved oxygen concentration lesser that 0.2 mg/L for denitrification and higher than 0.5 mg/L for nitrification is necessary. Sometimes physical/membrane treatment can be used. From the large range of membranes, classified by pore size, shape, material of construction or configuration, the selection is crucial depending on the wastewater to be treated. Similarly, for the treatment of high strength PSW multiple studies focus on the treatment using ultrafiltration with a pore size ranging from 0.002-0.1 microns which intern forms a barrier against pathogens and bacteria [24].

According to a study by Malmali *et al*. [24], membranes can offer absolute barriers to pathogens and contribute in terms of COD, TSS and FOG reduction, as Basitere *et al.* [25] found average removal of 64%, 88% and 48% respectively for these contaminants which assisted in achieving a total of 98%, 99.8% and 92.4%. Its known advantages also include:

a) Simplicity
b) No chemicals required
c) Compactness
d) Cost Efficiency [24]

To counter the permeation of pathogenic microorganisms due to unnoticed membrane fouling, ultraviolet is an effective disinfecting method that exposes the bacteria to UV radiation via lamps [24]. The pathogenic microbes namely; coliforms and *e-coli* present as a result of blood and faecal matter traces present in the poultry slaughterhouse wastewater are reduced to ±6 CFU/100mg and 0 CFU/100mg which far exceeds the set South African general limit for effluent discharge [26].

However, to achieve success in the secondary and tertiary stages and reduce the strain on the SGBR, SND and membrane operation offered by the fatty and nutrient rich nature of PSW, biological pre-treatment has been found as an effective method after screening. The combination of the pre-treatment that uses facultative microbes to reduce the hardwater and UV lamps on the hybrid-SGBR (with recycle), single-stage nitrification-denitrification and membranes can make an efficiently running plant that produces an effluent reduced not only of organics, solids and nutrients but pathogens as well.

2.4. Summary

The SGBR bioreactor, SND and UF membrane combination is a treatment combination which has been found effective. However, the poultry slaughterhouse wastewater highly contributes to bioreactor clogging and membrane fouling. The addition of the pre-treatment unit can hydrolyse some of the pollutants prior to release the units' effluent to the anaerobic reactor for effective AD functionality which will aid the improved performance a MBR. In the case of bed fluidization, the additional recycle can used to periodically expand the bed, lessening the clogging tendency of the reactor thus reducing channelling. As a last step, the UV lamps can safely rid the water of pathogenic microorganisms thus finally producing a quality effluent that far exceeds the set South African standards.

2.5. References

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CHAPTER THREE METHODOLOGY AND RESULTS

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CHAPTER THREE

3. Methodologies and Results: Assessment of an Integrated and Sustainable Multistage System for the Treatment of Poultry Slaughterhouse Wastewater

3.1. Introduction

Millions of litres of poultry slaughterhouse wastewater (PSW) are generated annually from a series of process steps used for bird processing for meat, which includes the slaughtering process, meat handling, and cleaning of facilities and equipment [1]. From this, the contaminated wastewater contains a high concentration of organic matter from blood, skin, fats, including nutrients and the chemical pollutants from detergents used to clean holding facilities, bird urine, and faecal matter, thus, making the disposal of this high-strength wastewater perilous [1,2]. Beyond the risks linked to the deterioration of the environment, pollution is one of the most pressing environmental health priorities requiring intervention. Similarly, the strength of PSW has been proven to be much higher than domestic wastewater and reduces water-dissolved oxygen, thus, affecting water-dependent species when released into receiving sources untreated [3,4]. While poultry slaughterhouses have employed wastewater treatment units, most are outdated and incapable of achieving suitable contaminant and nutrient reduction as per the set regulations. Overtime, the discharged wastewater may result in sewer line damage, the contamination of water bodies, the pollution of land, and the possible emission of harmful gases from the nutrients and contaminants contained therein [5]. Furthermore, the urgency for effective treatment methods for PSW lie not only in the need for continued wastewater treatment research but can have financial benefits due to the escalating growth demand for poultry products that is aided by the South African agro-economy expansion. However, for such growth to be sustainable, the devastating effect the wastewater has on the environment, growing water use, and demand, water conservation and recycling should be implemented worldwide. Hence, in the efforts to conserve water reserves in an already stressed water scarce country, i.e., South Africa (SA), researchers have since employed various technologies in the pursuit of effective PSW treatment options. All around the world, biological treatment systems have been explored for PSW treatment due to their efficiency, i.e., nutrient and organic matter removal abilities, using several technologies. Furthermore, these systems are appreciated for their simplicity and reduced hydraulic retention times (HRTs) while handling high organic loading rates (OLRs) [6]. These biological systems contain anaerobic, aerobic, or facultative microorganisms that degrade organics in the PSW [7,8]. However, others [9] substantiated the superiority of anaerobic digestion in comparison to aerobic digestion as a secondary treatment unit, whereby an aerobic system was compared to an anaerobic system in a comparative study using a series of case studies that looked at the up-flow anaerobic sludge blanket (UASB), an activated sludge process, among others. In addition, the study concluded that aerobic systems are recommended for post-treatment, particularly in bigger plants for nutrient removal and further PSW purification to meet the general limit for effluent discharge than as primary systems for PSW [9,10]. Furthermore, some [10] continued and attested aerobic technologies as better post-treatment technologies to best treat the solubilised organics in FOG laden effluent, utilising a system comprised of an anaerobic baffled reactor (ABR) seeded with activated sludge (AS). The study's observations attested to additional organic reduction from 128 and 132 mg/L to 0.1 and 0.4 mg/L for total organic carbon (TOC) and COD, respectively. In another research study by [11], an anaerobic–aerobic system using an EGSB coupled with a membrane bioreactor (MBR) was evaluated. The bioreactor achieved a COD average removal of 63% and, when combined with a MBR, an average of 96% removal was achieved, thus signifying that the anaerobic–aerobic set-up can be effectively used for PSW treatment. This was substantiated by [10], using a concept of pre and-post-treatment. The anaerobic process has limitations such as high temperature sensitivity, inability to efficiently remove nutrients, and depending on the configuration and operating conditions, clogging of the granular bed due to solids and FOG settling over the bed. Additionally, low to moderate effluent quality and longer start up periods from the acclimation period for the organic matter decomposing microorganisms, were identified as the main drawbacks [12]. Table 7 lists a summary of technologies used and the achieved COD, TSS, and FOG removal efficiency using the anaerobic reactors for the lipid-rich PSW treatments to date

Table 7. Achieved effluent quality from past studies for PSW treatment.

Reactor Technology	Year of Development	Reactor Development Rationale and Challenges	Performance Results	Reference
Expanded Granular Sludge Bed (EGSB)	-	Side recycle stream improves efficiency due to the increase in sludge expansion. Up-flow configuration resulted in sludge washout during high FOG and TSS loading, thus resulting in methanogen loss, which reduced biological degradation.	65% tCOD removal	[1]

Table 7 cont. Achieved effluent quality from past studies for PSW treatment. Cont.

Reactor Technology	Year of Development	Reactor Development Rationale and Challenges	Performance Results	Reference
Static Granular Bed Reactor (SGBR)	2000	An SGBR with a down flow configuration was developed. Challenges include clogging of the underdrain. Hence, requiring periodic alleviation through backwash, disturbing the underdrain and granular bed build-up.	95% COD removal, 95% TSS removal, 90% FOG removal	[13,14]
Down-flow Expanded Granular Bed Reactor (DEGBR)	2019	A hybrid of EGSB and SGBR, with down/top feeding configuration and a recycle.	99,6% COD removal, 93,7% FOG removal	[8]

Despite the positive advances taken, several researchers found that high protein wastewater (such as PSW) results in the production of free ammonia during anaerobic digestion [13]. They recommended a pre-treatment stage to treat the wastewater characteristics for enhanced anaerobic digestion (AD) performance without producing detrimental by-products such as ammonia. Additionally, the authors of [10] indicated that anaerobic processes require pre- and post-treatment steps for the appropriate removal of solids, nutrients, and FOG that tend to clog the AD reactor and piping system thereof, resulting in a reduced reactor performance and an accelerated reactor failure. Furthermore, in up-flow reactors, periodic sludge washout due to suspended solids and high lipid content has been observed [1,12].

To date there have been several pre-treatment methods developed from the findings conducted for AD. Table 8 lists a summary of the effective pre-treatment methods coupled with AD in numerous studies. From the results, it is also evident that a pre-treatment unit can remove some of the contaminants.

Table 8. Developed pre-treatment technologies and their COD, FOG, and TSS removal efficiency.

Pre-Treatment Technology	Reactor Coupled with the Pre-Treatment Unit	Limitations	Performance Results	Study of Reference
Thermal Autoclaving	-	Additional physical separation of the clear liquid and semi solid sludge is necessary.	81% COD removal, 59% FOG removal, 43% TSS removal.	[14]
Chemical Dissolved Air Flotation (DAF)	UASB	System showed instability due to the varying PSW influent. Additionally, system efficiency is highly affected by chemical used.	43% ± 15% suspended solids (SS) removal and 49% ± 8% oil and grease (O&G) removal.	[15]
Biological Enzymatic Pre-treatment	-	Optimal enzyme dose is not yet established. Though the increase in dose results in increased free fatty acid and VSS treatment, the dose has an optimal point where higher doses do not contribute to increased effectiveness.	Increase in free fatty acids and 10% hydrolysis promotion due to lipase, 88% COD reduction in PSW.	[13,16,17]
Hydrodynamic Cavitation	-	Optimum conditions included addition of Fenton reagent.	Increased COD treatment to 44,2%. Biological oxidation treatment time reduction from 60 to 36 h.	[18]

Similarly, there are post-treatment technologies that can be used, among which membrane bioreactors are the most researched. These reactors sometimes consist of activated sludge and membranes that contain distinct pores that remove dissolved organic and inorganic contaminants by providing a physical barrier that filters out pollutants and bacteria [19]. Many studies have included membrane bioreactors as a tertiary treatment stage achieving exceptional results as high as 98–>99% removal efficiency [19,20].

Similarly, post AD, a membrane unit was installed for the further purification of the formed by-products during the AD process [8], subsequently assisting in the further remediation of the wastewater. Submerged membranes are well known for fouling primarily in high FOG wastewater such as that from poultry slaughterhouses. As per the Membrane Bioreactor Task Force of the Water Environment Federation (WEF) (2012), MBR requires coarse influent screening, grit removal, fine screening, and primary clarification, all of which are pre-treatment technologies. Therefore, studying the effectiveness of a combined pre-treatment, an AD bioreactor, and a submerged membrane system is, therefore, crucial for this study. As shown in Figures 7 and 8, a set-up as illustrated was used in this study for the treatment of PSW.

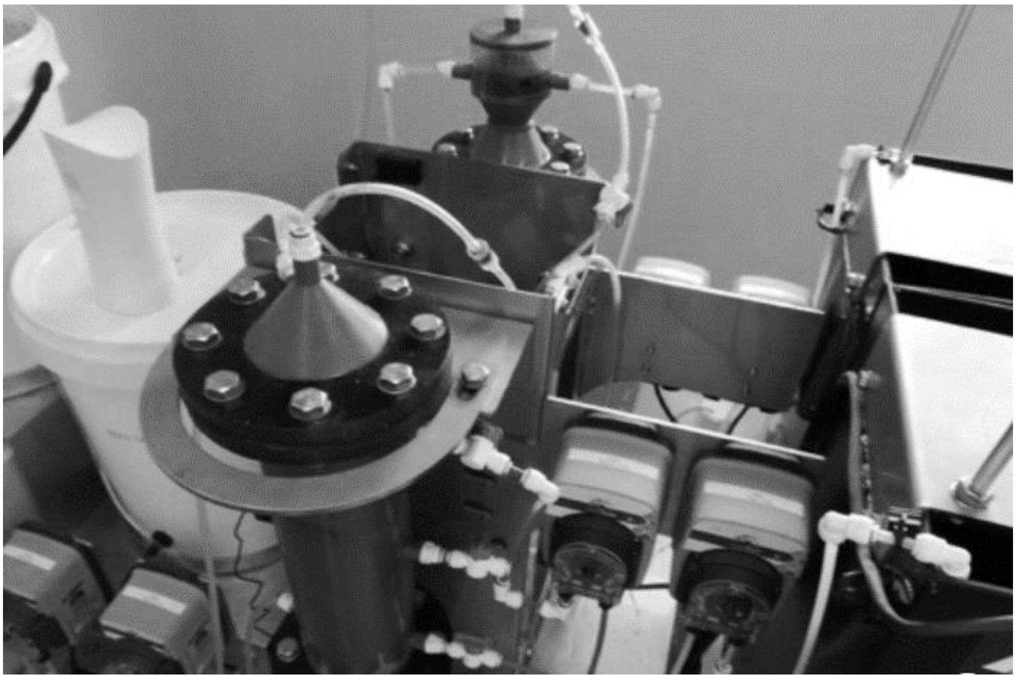


Figure 7. Lab-Scale Treatment Plant for PSW [21]– Reprinted from Membranes, vol 11, Meyo, H.B.; Njoya, M.; Basitere, M.; Ntwampe, S.K.O.; Kaskote, E., “Treatment of Poultry Slaughterhouse Wastewater (PSW) Using a Pretreatment Stage, an Expanded Granular Sludge Bed Reactor (EGSB), and a Membrane Bioreactor (MBR)”. Copyright (2021), with permission from MDPI.

From previous studies, the recommendations included a thorough pre-treatment step to rid the PSW of solidified FOG in order to enhance the AD reactor's performance [1,22]. From the identified gaps, this research included a performance review on a biological pre-treatment stage using a commercial product, i.e., Eco-flush^{TM} as an additive providing active enzymes for FOG hydrolysis. With the pre-treatment process in place, this study further investigated the performance of the treatment of PSW after the FOG reduction in the pre-treatment unit. Furthermore, the efficacy of the MBRs as a post treatment technology was also investigated. Lastly, the performance of the full pre-treatment, AD, and MBR chain was investigated

3.2. Materials and Methods

3.2.1. PSW Sampling

PSW was collected from a local abattoir in the Western Cape, SA. The sample was drawn from an in-between slaughtering process and wastewater processing stage to acquire a representative raw PSW sample. For preservation, the wastewater was stored in a temperature-controlled unit at 5 °C. A representative sample was taken to study the COD, TSS, and FOG of the raw incoming PSW in comparison to the established raw PSW average conditions, as shown in Table 9.

Table 7: PSW Characteristics

Parameter	Units	Minimum	Maximum	Average	Reference	This Study
COD	mg/L	4100	9100	4317	[24]	6500 - 21000
TSS	mg/L	1580	3750	2800 ± 950	[24], [25]	2985 - 8363
FOG	mg/L	280	8228	1655 ± 1880	[8]	640 - 4500

3.2.2. Experimental Set-up

The set-up configuration is as shown in Figure 8. All the units had biogas collection ports, although this did not form part of this study.

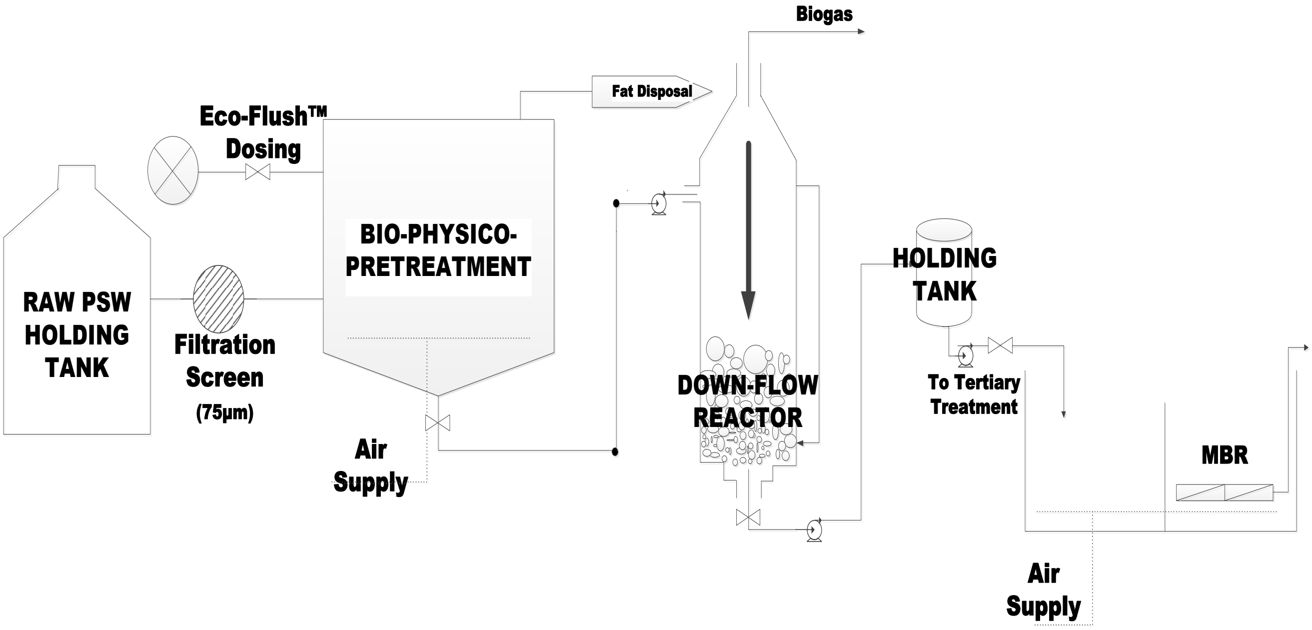


Figure 7: Process Flow Diagram of the Treatment Plant

3.2.3. Pre-treatment Unit Set-up

The PSW was pre-treated by dosing 20 mL of Eco-Flush^{TM}, supplied by Mavu Biotechnologies (Pty) Ltd., into a 20-litre pre-treatment tank with raw PSW. The Eco-Flush^{TM} contained a complex mixture of microorganisms, including aerobic, anaerobic, nitrifying, and sulphur oxidising bacteria combined with fungi and enzymes associated with the hydrolysis of FOG, i.e., the dissociation of bonds between the triglycerides and phospholipase resulting in a glycerol and fatty acid separation. Furthermore, not only does Eco-Flush^{TM} aid the reduction in FOG content in PSW, it also contains a bacterial mixture that synergistically produces enzymes (in a nutrient rich environment) that accelerate the decomposition of organic matter and oxidation of ammonia into nitrates and nitrites [25].

A Resun air pump (Ac 9906) from Hydroponic in Cape Town, South Africa, was used to sparge air into the pre-treatment tank using silicone tubing. The silicone tubing used to pump air into the pre-treatment tank was connected to two diffusers to provide sufficient micro-bubble formation into the system. This ensured that there was an adequate dissolved air supply to create the optimum conditions for aerobic bacteria to be most effective. The mixture was aerated for 24 h then allowed to settle for a further 24 h to allow the Eco-Flush^{TM} time to adequately digest the FOG and decouple proteins within the PSW and to reduce the level of H_2S, which is known to deactivate anaerobic bacteria. The pre-treated PSW was then filtered with a 75-micrometre Madison Test sieve into a pre-treatment tank, which feeds into both the EGSB (previous study and for comparison) and DEGBR. The PSW to the AD systems was continuously stirred with a stirrer to keep the feed in a homogeneous state. The treatment process is depicted in Figure 9.

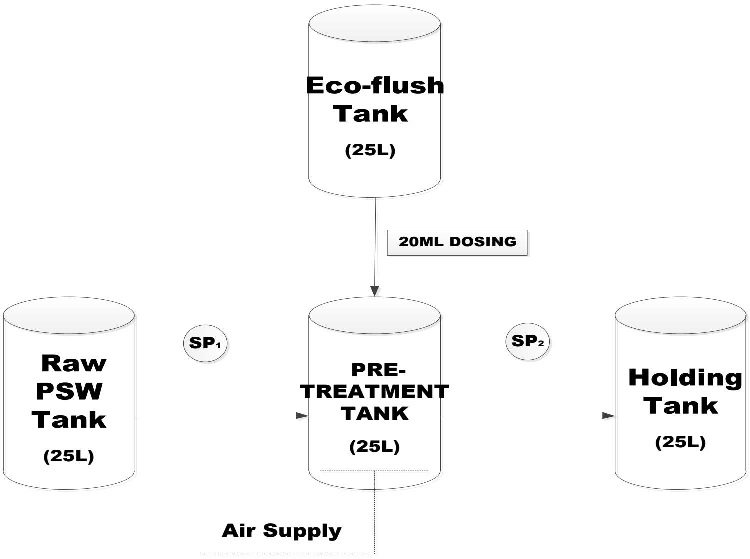


Figure 8: Pre-treatment Experimental Set-up

3.2.4. Bioreactor Experimental Set-up

Lab scale (2L) Polyvinylchloride (± 600 x 110cm) DEGBR and EGBS reactors, were simultaneously set-up parallel to each other as illustrated in Figure 10. Each reactor was connected to a feed holding tank containing pre-treated filtered feed from the Eco-flush^{TM} pre-treatment unit (Illustrated in Figure 4).

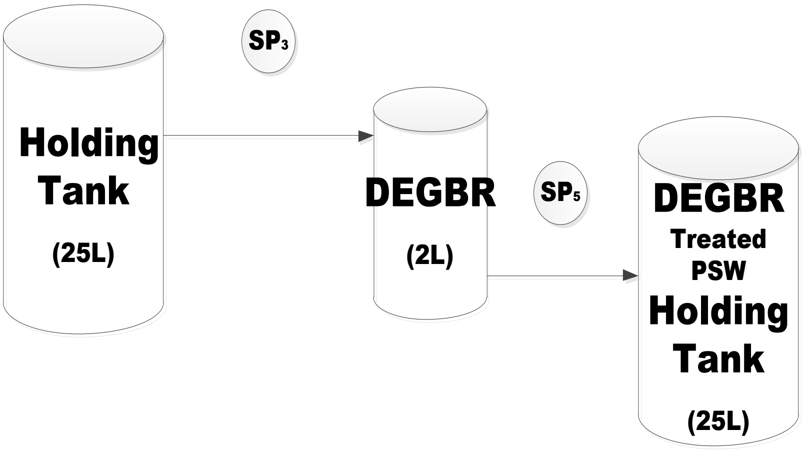


Figure 9: Reactor (DEGBR) Set-up

The reactor was inoculated with anaerobic granules from an USAB operated at a local brewing house situated in Newlands, Cape Town. A volume (200 mL) of 50% v/w dry milk was used as a source of carbon and was fed to the granules, to assist with the acclimation of the anaerobic biomass. For optimal acclimation, mesophilic temperatures (29–36 ◦C) were maintained by connecting an external water bath to the reactors jacket. Reactor inoculation took a period of 72h prior to running the reactors at 0.36L/h and had a HRT of 5.71hr. Product released was stored in separate holding tanks for individual performance analysis conducted at an SANAS-accredited external laboratory, i.e., City of Cape Town Scientific Services.

3.2.5. Membrane Bioreactor Units Set-up

- Membrane Bioreactor design

Hydrophilic polyethersulfone (PES) membranes with a 0.04-mirometre pore size and a glycerine (20%)/sodium benzoate (3%) preservative were housed in a 315×182×69 mm polyvinyl chloride (PVC) module with a polyester (PET) drainage layer. The casts were submerged in 100 L aerated tanks, as illustrated in Figure 11.

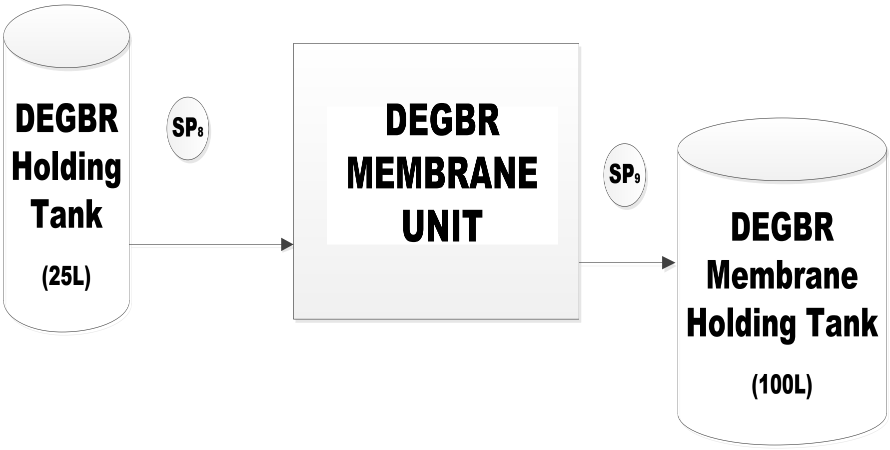


Figure 10: Membrane Bioreactor Unit Set-up

- Inoculation and Operating Conditions

A volume (25L) of AD treated PSW was filled in each tank. The aerated MBR systems acclimatised for a period of 48hrs prior to the filtration cycle start-up at low flow rates of 0,36L/hr. The observed operated conditions included a temperature range of 5-40 °C and pH range of 2-11.

3.2.5. Sampling Points and Analysis

The sample point is as demonstrated in Figure 9 as SP_2. Samples of the pre-treated PSW were taken every second day, while sampling points for the DEGBR were collected from SP_3 and SP_5, respectively, as illustrated in Figure 10. After the MBR was inoculated, the samples for the DEGBR-MBR systems were collected weekly at SP_9, as shown in membrane set-up unit (Figure 11).

Once collected, the samples were stored at cooling storage at 5 °C to avoid acidification prior to analysis. See Table 10 for methods.

Table 8: Sample Analysis Methods

Parameter	Method
Temperature	EPA method 9040C
Total suspended solids (TSS)	EPA method 160.2
Total chemical oxygen demand (tCOD)	EPA method 410.4
Fats, oils and grease (FOG)	EPA method 10056

3.3. Results and Discussion

3.3.1. Pre-treatment Performance Evaluation

The development of the treatment plant used for this study included the Eco-flush^{TM} dosed bio-physico aerated pretreatment unit that encouraged FOG coagulation and hydrolysis, which reduced the risk of FOG accumulation in the reactor bed and piping system [25]. After the 24-h aeration period, the enzyme activity had facilitated the effective separation of glycerol from the lipid-rich PSW through hydrolysis, thus, corroborating research from other studies [13], whereby it was concluded that hydrolysis promotion was evident in the Eco-flushTM dosed pre-treatment unit, hypothesised to be facilitated through lipase action. Figure 12 depicts the pre-treatment operation and FOG collected after coagulation.

(a) During pre-treatment

(b) Collected coagulated FOG after pre-treatment

Figure 11: (a) Eco-Flush^{TM} dosed pre-treatment during and after 24hr aeration when the enzymatic pre-treatment is employed, (b) The coagulated FOG collected from the top of the pre-treatment unit.

The performance of the pre-treatment stage used in this study is illustrated in Figure 12, which depicts the variation of key water quality assessment parameters as well as their removal efficiencies throughout the study. These parameters were not pre-processed to exclude outliers that may have been identified during the experiment. To identify these outliers, boxplots (see Figure 13a) were used. According to Figure 13a, outliers were identified in the distribution of the inlet FOG and COD, as well as the outlet COD. These outliers can be less clearly observed in Figure 12, which depicts the variation of these parameters throughout the study. To identify these outliers, the interquartile range rule was used, and they were, subsequently, replaced by the median value of respective distribution to correct the effects of the outliers.

The box plot redacted performance profile of the PSW pre-treatment stage is displayed in Figure 13, from which it can be observed that this treatment stage performed well for the removal of FOG (65 to ~92%) and TSS (~45 to ~72%), with an insignificant removal of COD (~25 to ~52%) in comparison to the literature [13,16,17]. An evaluation of a possible correlation between these removal efficiencies was conducted in Figure 15, which depicts a correlation matrix with Pearson's correlation coefficient (r) and the p-value for hypothesis testing. Usually, an R-value above 0.75 translates to a considerable correlation between the assessed parameters, which can be confirmed with a p-value ≤ 0.05. However, the removal values displayed in Figure 15 showed no correlation between the COD, FOG, and TSS removal efficiencies for the pre-treatment unit.

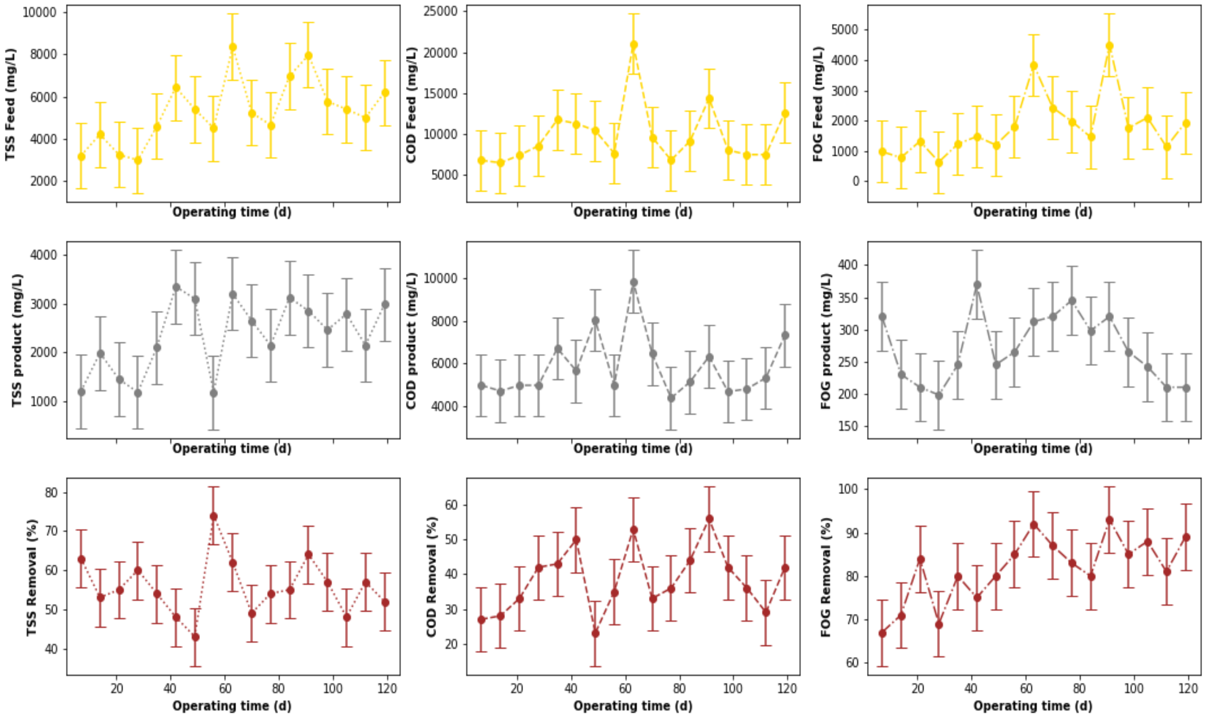


Figure 12: Performance of PSW pre-treatment stage before outliers' detection and replacement

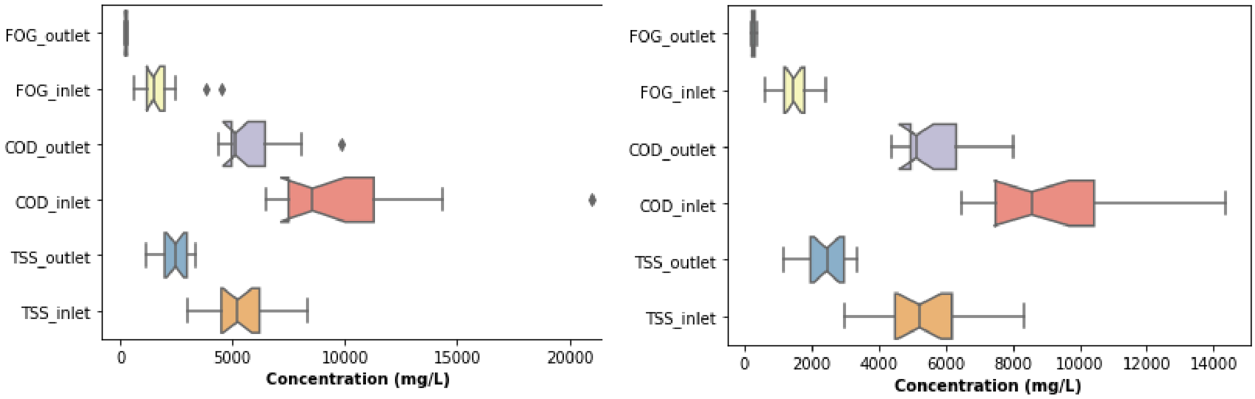


Figure 13: Boxplots of highlighted features before and after outliers' replacement: (a) Boxplots before outliers replacement; (b) Boxplots after outliers replacement.

The boxplot redacted performance profile of the PSW pre-treatment stage is displayed in Figure 13, from which it can be observed that this treatment stage performed well for the removal of FOG (65 to ~92%) and TSS (~45 to ~72%), with an insignificant removal of COD (~25 to ~52%) in comparison to the literature [13,16,17]. An evaluation of a possible correlation between these removal efficiencies was conducted in Figure 15, which depicts a correlation matrix with Pearson's correlation coefficient (r) and the *p*-value for hypothesis testing. Usually, an R-value above 0.75 translates to a considerable correlation between the assessed parameters, which can be confirmed with a *p*-value ≤ 0.05. However, the removal values displayed in Figure 15 showed no correlation between the COD, FOG, and TSS removal efficiencies for the pre-treatment unit.

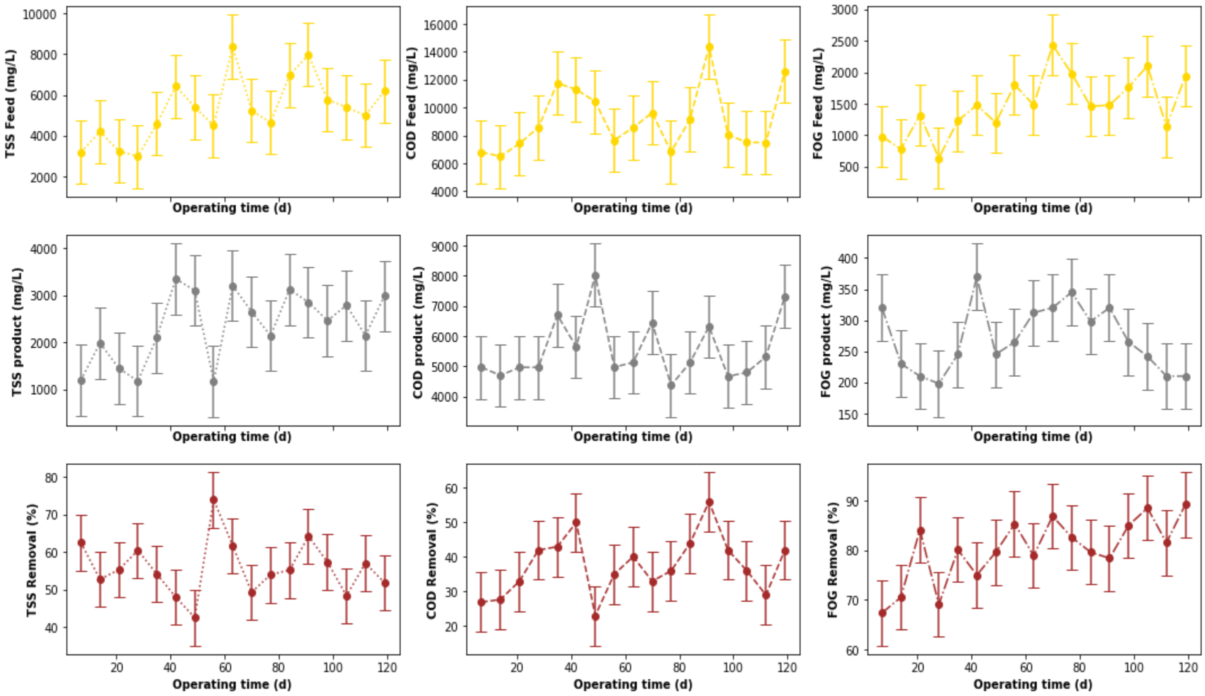


Figure 14: Performance of PSW pre-treatment stage after outliers' detection and replacement

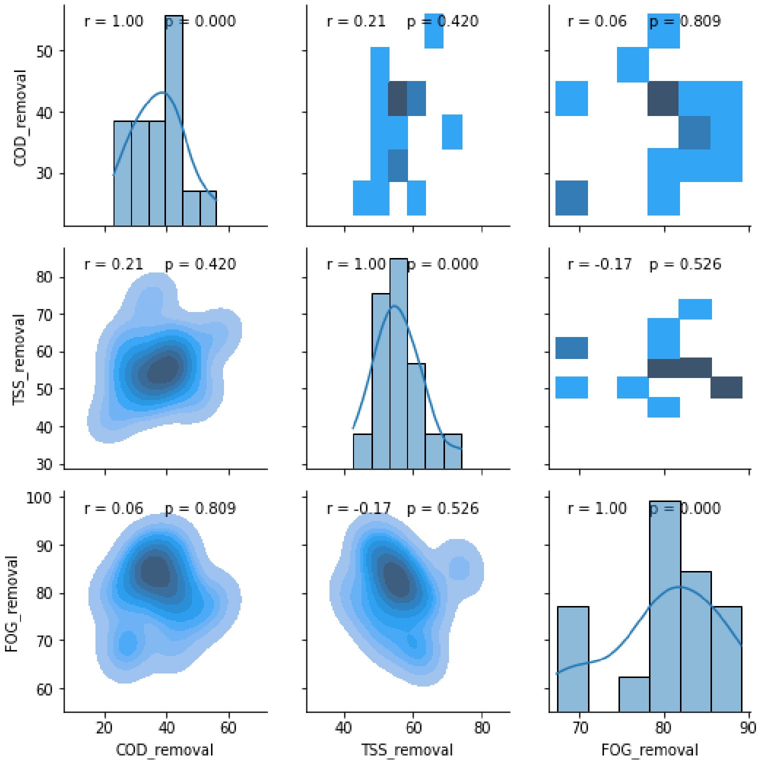


Figure 15: Correlation matrix between removal efficiencies of the pre-treatment stage

A further evaluation of the distribution of the removal efficiencies is depicted in Figure 16, which provides the density distribution, the skewness, the kurtosis, and the mean of the COD, TSS, and FOG distributions. Overall, as initially intended, the pre-treatment stage performed the best for FOG removal as designed, with a mean FOG percentage removal of 80% (see Figure 16), while the mean percentage removal of the COD and TSS, were 38 and 56%, respectively. The skewness of each of these distributions was low, but varied with different kurtosis values, as depicted in Figure 16.

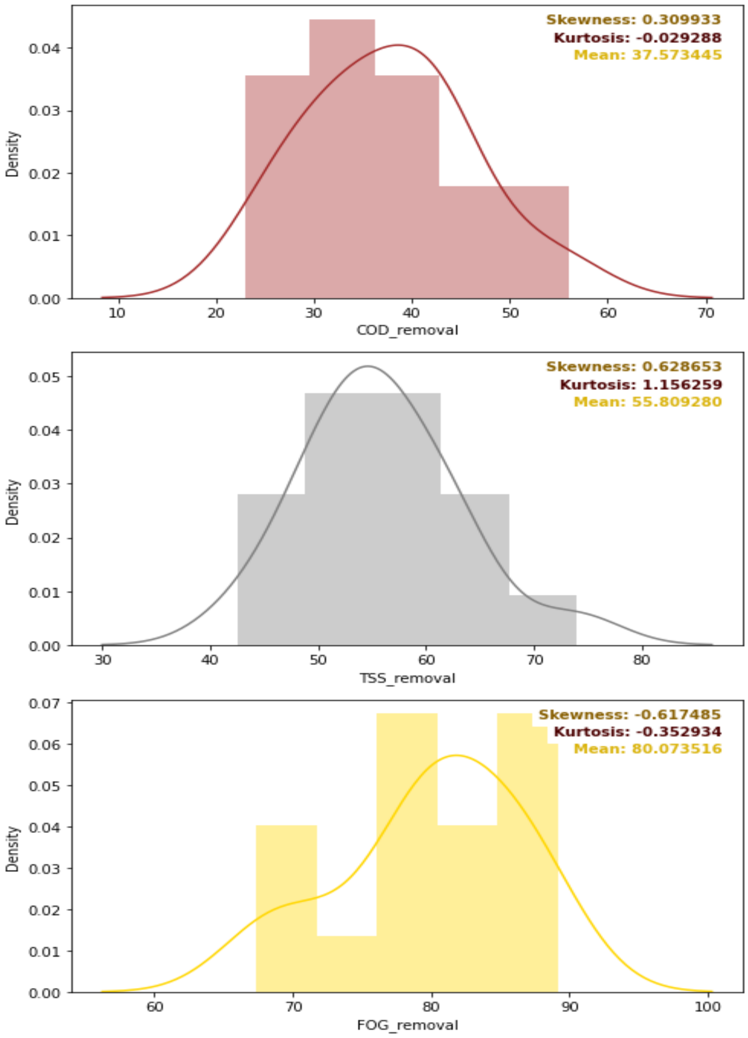


Figure 16: Density distribution, skewness, kurtosis, and mean values of the removal efficiencies of the pre-treatment stage

3.3.2. DEGBR Treatment performance

The output from the pre-treatment stage was separated into two streams. The first was supplied to the DEGBR, and the second to the EGSB. The output from both bioreactors was further treated separately using MBR systems receiving AD-treated effluent from both system types. Therefore, this section of the study evaluated the performance of the DEGBR as a secondary stage for the treatment of PSW. The variation of the assessment parameters used to conduct this evaluation is depicted in Figure 17, whereby the removal efficiencies above 65 to ~95% were noticed for each water quality parameter evaluated (COD, FOG and TSS), which exceeded the FOG removal attained by previous studies [8]. To further consolidate these observations, the presence of outliers was also evaluated using boxplots, as depicted in Figure 18a, whereby the presence of outliers in the distribution of TSS concentrations was observed in the outlet stream, while for FOG concentrations, outliers were observed in the inlet stream. As in the previous section, these outliers were replaced by the median of the individual quality parameter distribution to produce distributions without outliers, as depicted in Figure 18b. The replacement of these outliers resulted in a reliable distribution depicted in Figure 19.

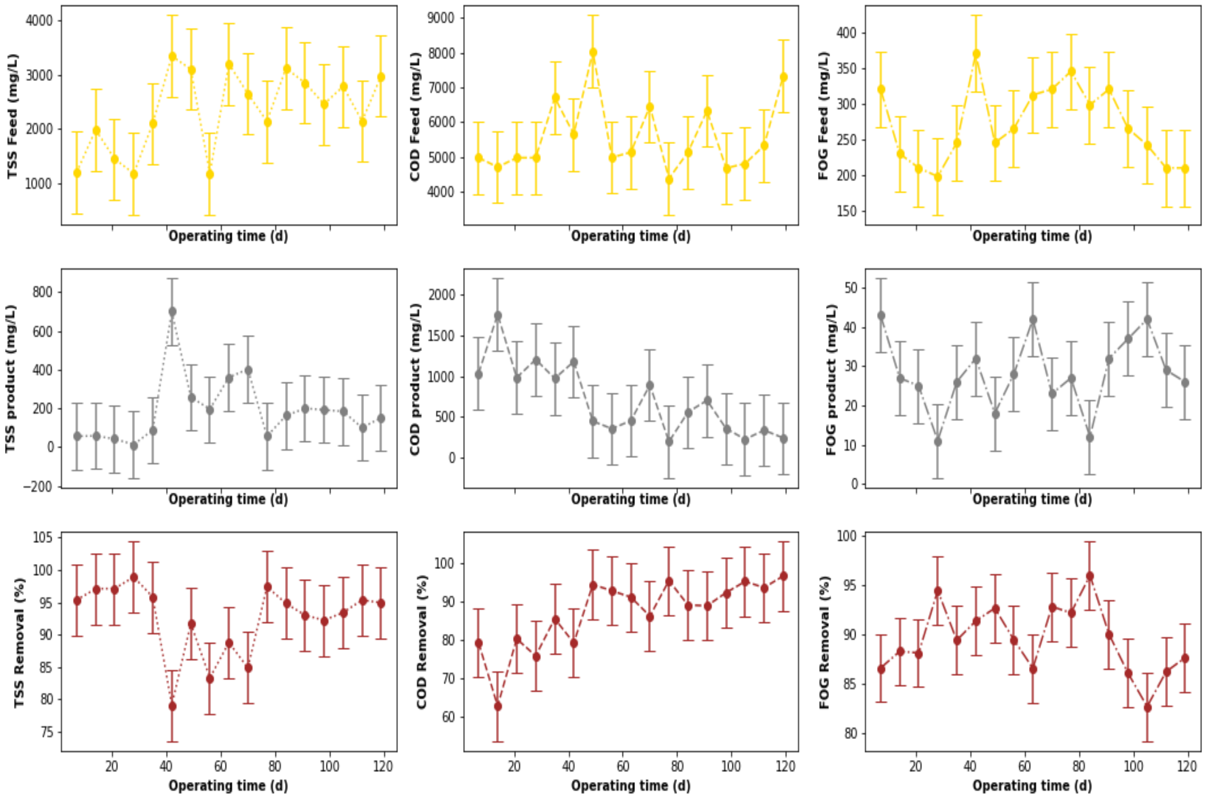
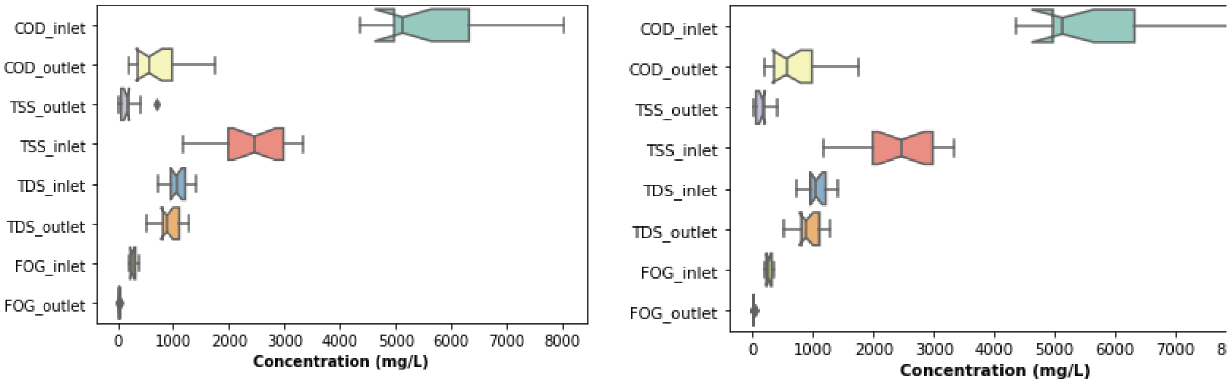


Figure 17: Performance of PSW DEGBR before outliers' detection and replacement



(a)

(b)

Figure 18: Boxplots of the DEGBR highlighted features before and after outliers' replacement: (a) Boxplots before outliers replacement; (b) boxplots after outliers replacement

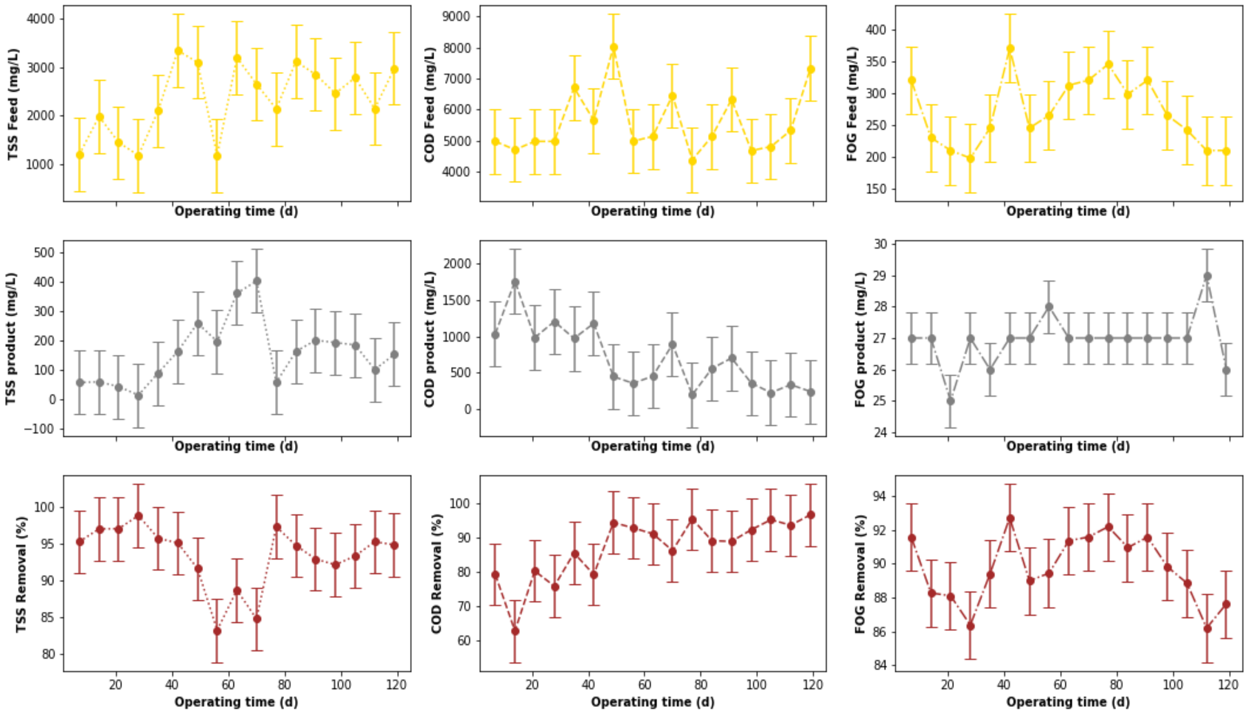


Figure 19: Performance of PSW DEGBR after outliers' detection and replacement

A comparison of the removal efficiencies varied throughout the study (see Figure 19) with indications that there was a slight change in the removal efficiencies between days 40 to 75 for the TSS removal. The alteration of the performance of the DEGBR for the removal of TSS was reduced during days 56 to 70. An improvement in the performance of the DEGBR after the outlier replacement was also noticed with the removal of FOG during days 14 to 28, and 102 to109. At this stage, it was not clear as to the reasons why the observed changes were observed, which is an indication that further analyses are required. The performance of the DEGBR was further assessed for relatedness, as shown in Figures 17–19, which showed the response of the DEGBR in terms of the removal of the FOG, COD, and TSS, respectively, when a variation of the OLR was implemented in the experiment. A comparison of these graphs shows a better response of the DEGBR for the removal of COD, despite the various fluctuations of the OLR varying from ~18 to ~45 g COD/L.d. Despite a good consistency in the evolution of the COD removal efficiencies, the DEGBR performance was higher at the beginning of the process for both the TSS and FOG removal efficiencies, as displayed in Figures 20 and 22, with ranges varying between ~84 and ~98% for the TSS removal, and ~85% and ~93% for the FOG removal, which is an indication that the AD bed acted as a bio-filter, perhaps with some hydrolysis capacity.

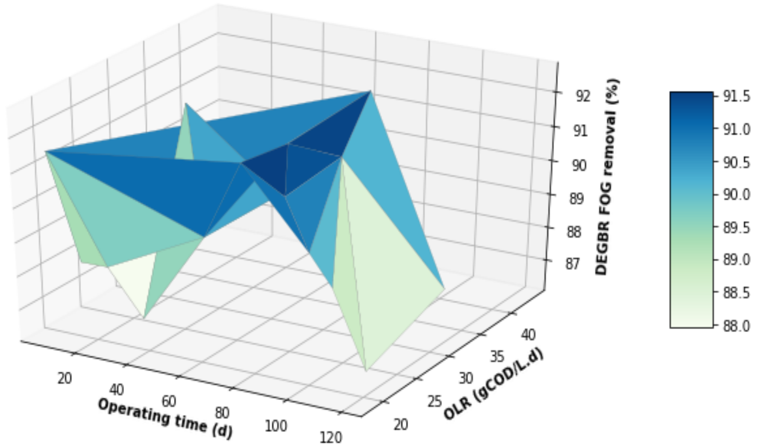


Figure 20: DEGBR FOG removal with respect to the operating time and the OLR

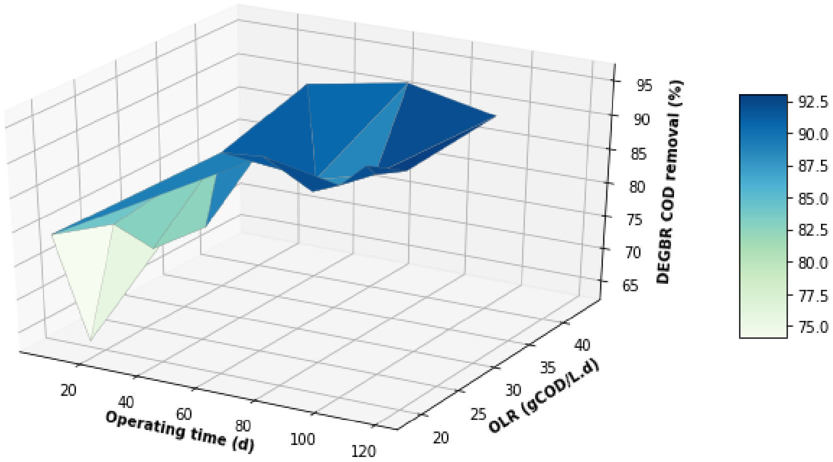


Figure 21: DEGBR COD removal with respect to the operating time and the OLR

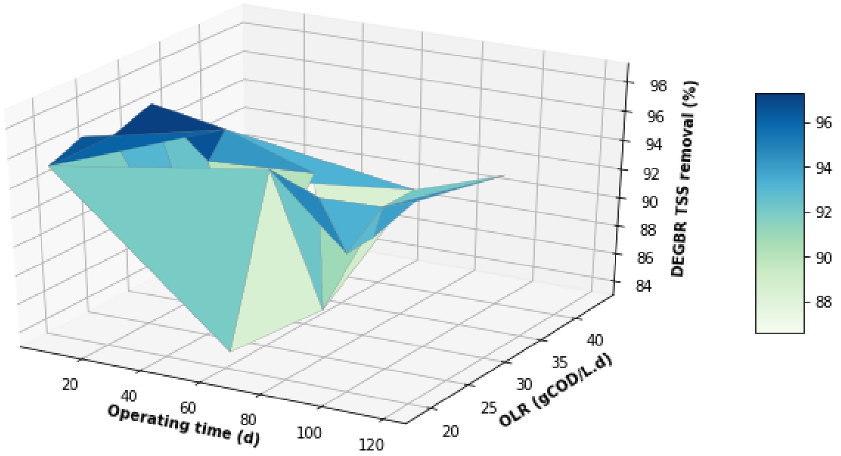


Figure 22: DEGBR TSS removal with respect to the operating time and the OLR

A feasible correlation between these removal efficiencies from the DEGBR treatment was evaluated using a correlation display, as illustrated in Figure 23. The latter shows a minimal correlation between the COD, FOG, and TSS removal efficiencies, as demonstrated by the low Pearson's correlation coefficients. A further evaluation of the quality of the distribution of each of these removal efficiencies as well as the mean of each distribution is depicted in Figure 24. From the latter, it can be seen that the DEGBR performed the best for the removal of TSS with a mean removal percentage value of 93%, followed by the FOG mean removal percentage with an averaged value of ~90%, and the COD mean removal percentage with a value of ~87%. The distribution of the removal efficiency values was more skewed and tailed for the TSS and the COD removal, and less skewed and tailed for FOG removal; overall, the DEGBR displayed a good performance for the removal of these contaminants, which were further removed in the post-treatment stage using an MBR.

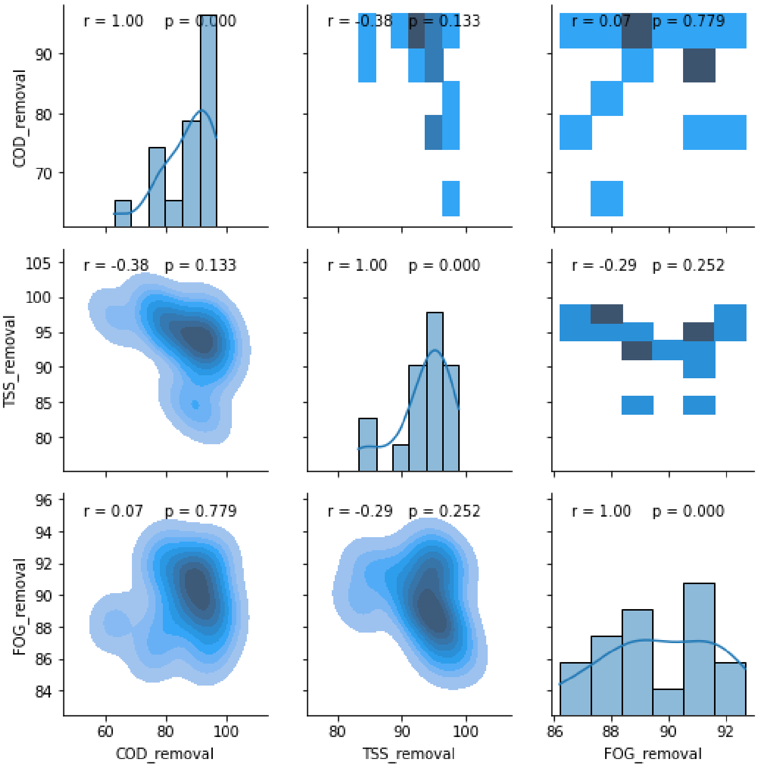


Figure 23: Correlation matrix between removal efficiencies of the DEGBR

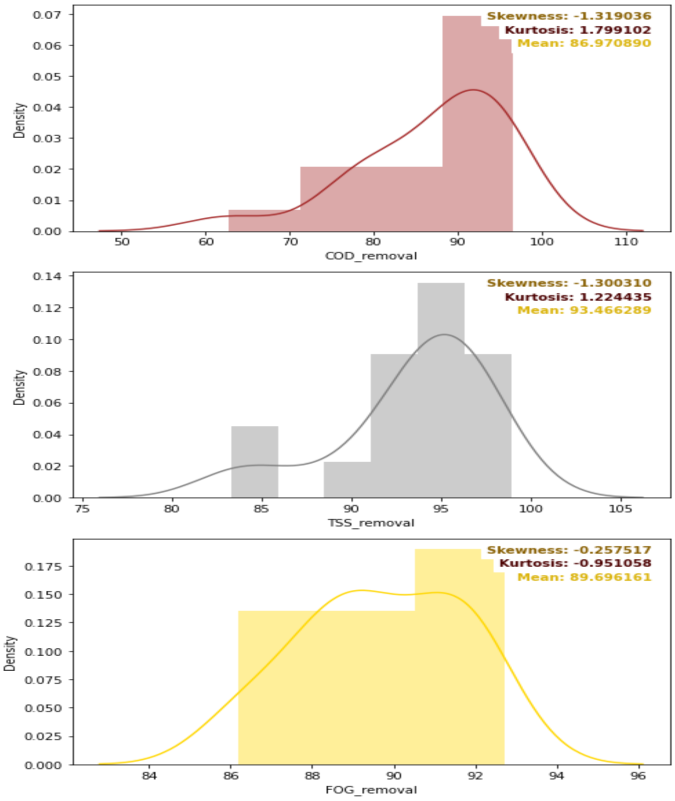


Figure 24: Density distribution, skewness, kurtosis, and mean values of the removal efficiencies of the DEGBR

With reference to the reactor limitations and rationale mentioned in Table 8, the observed DEGBR performance displayed an improved performance with no signs of clogging nor need for backwashing [13,14,22].

3.3.3. DEGBR-MBR Post-treatment

A post-treatment stage consisting of an MBR was coupled to the DEGBR to further decrease the concentration of contaminants from the PSW. Figure 25 provides the variation of the concentration of the TSS, COD, and FOG both at the inlet and outlet of the MBR throughout the study. The boxplots of the assessed parameters reveal that there were no outliers in each distribution investigated, which indicated the consistency in the performance of the MBR unit. The removal efficiency values of the TSS remained consistently high after day 42 of operation, while an inconsistent variation was noticed for the COD and the FOG, albeit with minute variations. Similarly, to the DEGBR, a minimal correlation was found between these removal efficiencies, as depicted in Figure 26. Figure 27 provides the density distribution, the skewness, the kurtosis, and the removal efficiency values from the MBR unit. A comparison between Figures 19 and 25 shows that the DEGBR performed better than the MBR unit in terms of removal efficiency of the TSS and FOG. The MBR unit performed slightly better than the DEGBR for the mean removal efficiency of the COD, indicating its suitability as a polishing stage, i.e., the MBR unit performance significantly improved the quality of the treated PSW and contributed to the improved overall performance of the system composed of the pre-treatment stage, the DEGBR, and the MBR units. As shown in Figure 28, it can be observed that the performance of the overall process was >98% throughout the study.

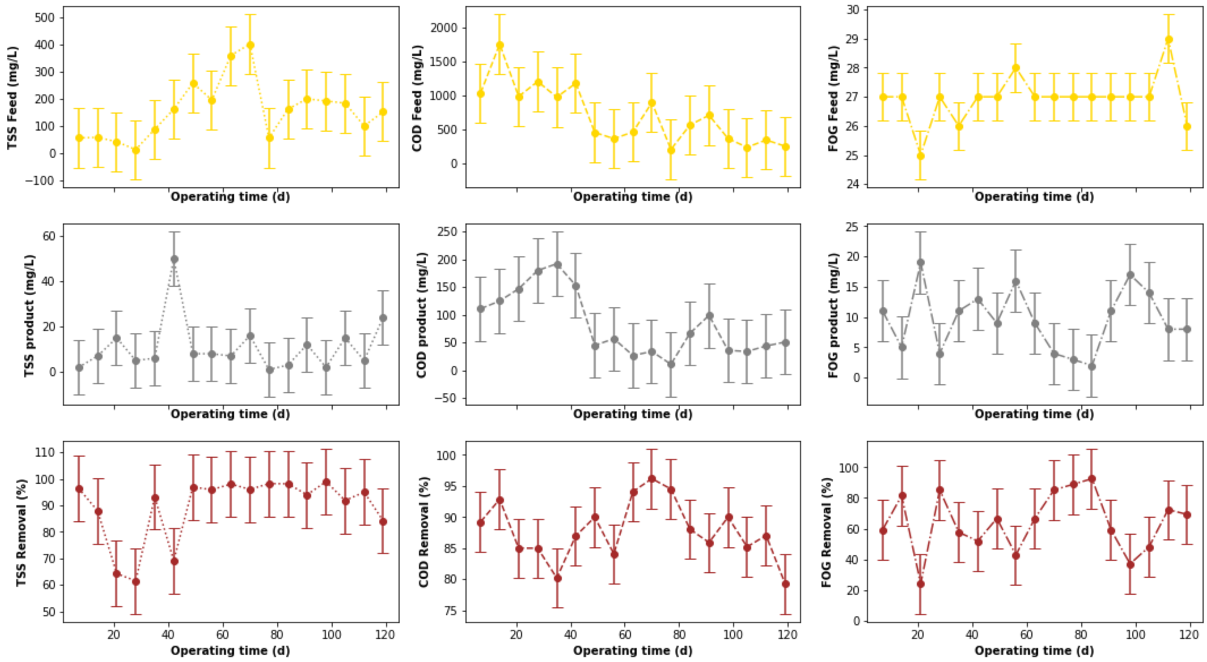


Figure 25: Performance of the MBR after the DEGBR treatment

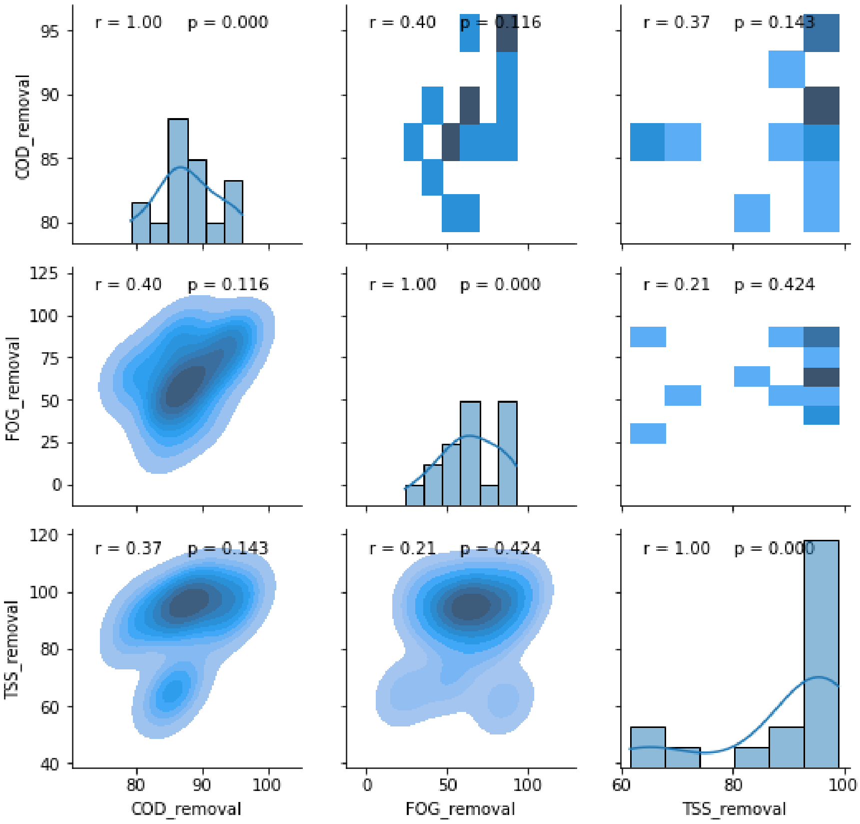


Figure 26: Correlation matrix between removal efficiencies of the MBR after DEGBR treatment

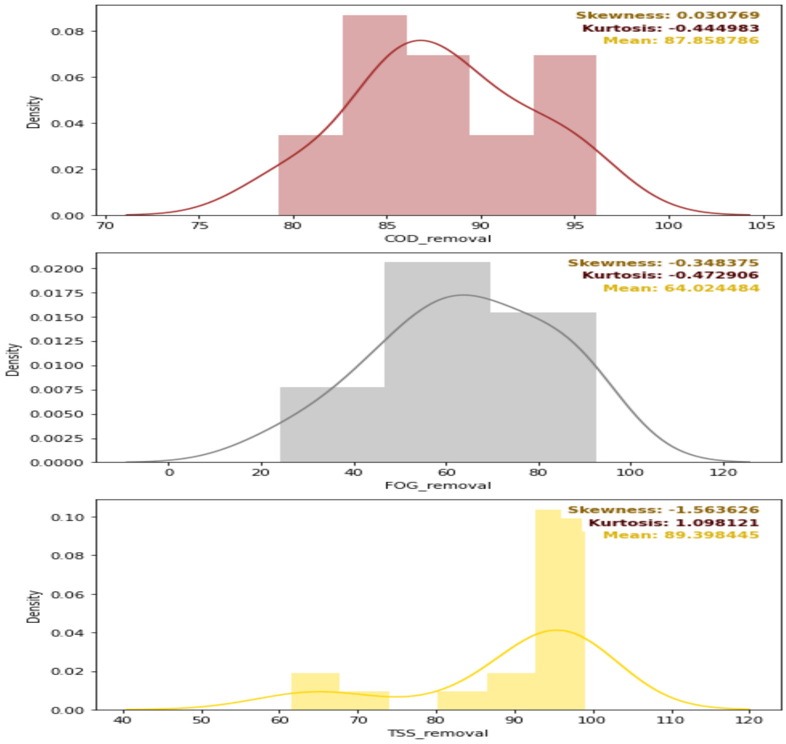


Figure 27: Density distribution, skewness, kurtosis, and mean values of the removal efficiencies of the MBR after DEGBR treatment.

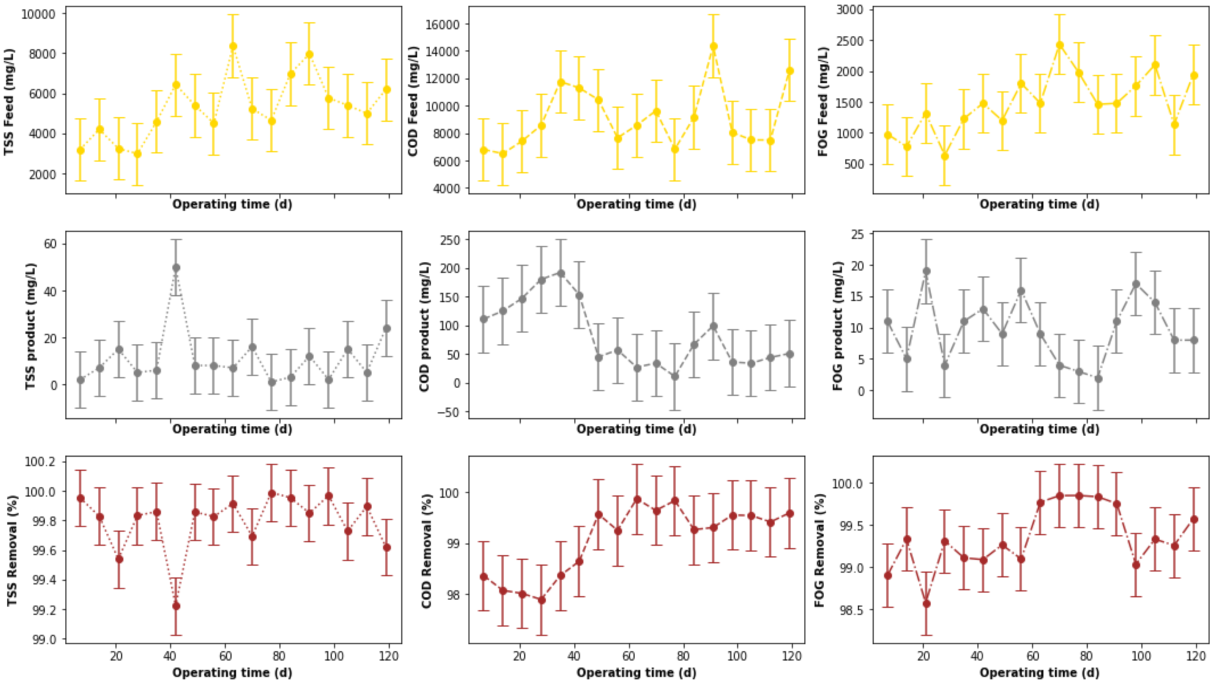


Figure 28: Overall performance of the combination of the pre-treatment stage, the DEGBR, and the MBR.

3.3.4. Overall Performance of pre-treatment-DEGBR-MBR system

The overall performance of the integrated system combining a pre-treatment stage, the DEGBR, and the MBR is provided in Figure 28. This indicated a commendable performance of the system, with overall removal efficiency values of the FOG, COD, and TSS being >98% throughout the study. Although, Figure 29 indicated a minimal correlation between the removal efficiency of the FOG, COD, and TSS in the overall system, highlighting the suitability of such a system for the treatment of PSW or similar type of wastewater. The integration of different stages in the process addresses the shortcomings that one stage may have, and this can lead to overall potable water savings and perhaps the reuse of the treated water for other purposes such as irrigation, which, at this stage, still needs to be evaluated.

Figure 30 provides the density distribution, the skewness, the kurtosis, and the removal efficiency values of the combination of the pre-treatment stage, the DEGBR, and the MBR. A comparison between Figures 25 and 28, Figure 30 shows that the increased removal efficiency of the combined pre-treatment-DEGBR-MBR approach which resulted in FOG, TSS and COD removal higher than 99%. Despite these results signifying a positive membrane unit functionality, circumventing the typical membrane challenges such as clogging and membrane fouling, there was evident foam build-up during aeration. Furthermore, biofilm formed at the bottom of the membrane unit when an EGSB was used (shown in Figure 31a). The MBR operation was stopped after operating for 5 weeks due to signs of extracellular polymeric substances (EPS) build-up, as shown in Figure 31b. Thus, validating a re-evaluation of the sludge retention times (SRT) and aeration rate cited in some MBR operations [26] with excessive aeration being required, while extremely low SRTs were required due to the increased EPS in the MBR downstream. This presented a challenge that needs to be addressed in subsequent studies

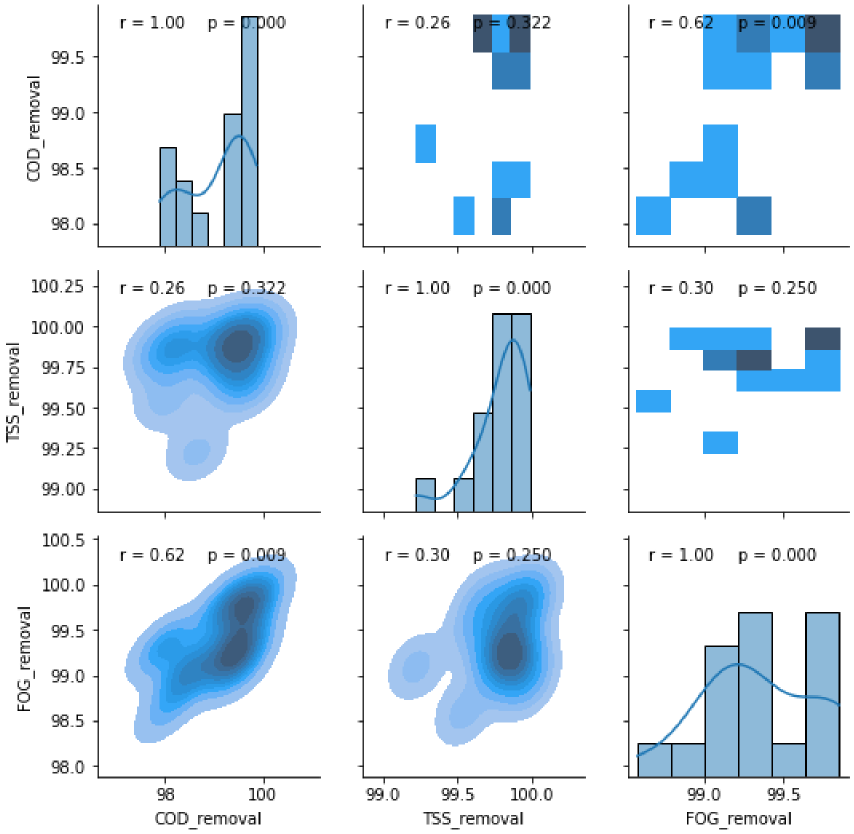


Figure 29: Correlation matrix between removal efficiencies of the combination of the pre-treatment stage, the DEGBR, and the MBR.

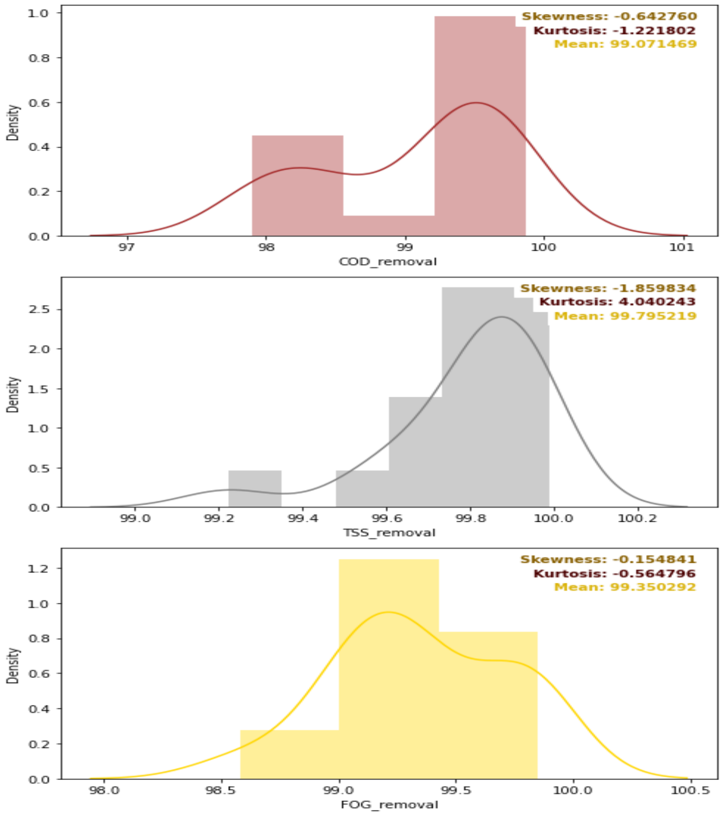
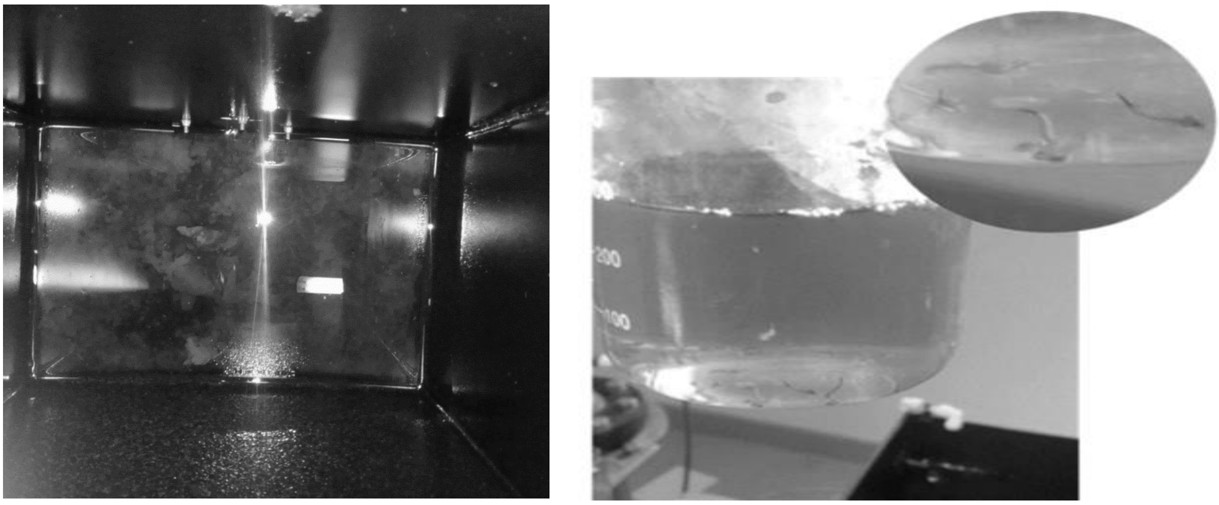


Figure 30: Density distribution, skewness, kurtosis, and mean values of the removal efficiencies of the combination of the pre-treatment stage, the DEGBR, and the MBR.



(a) (b)

Figure 31: a) Biofilm at the bottom of the membrane; (b) Membrane sample during treatment.

3.4. Summary

The use of a commercially viable bacterial suspension has provided a significant impactful FOG remediation strategy for PSW treatment, especially with regard to FOG removal. The study investigated the effectiveness of the implemented bio-physico-pretreatment process, which has been proven to show a significant FOG concentration removal of 80%, which, in turn, aided the AD reactor performance. Furthermore, this study also evaluated the Pre-treatment-DEGBR-MBR unit set-up in the form of a laboratory-plant for PSW treatment. The DEGBR achieved effective PSW containment removal at an HRT of 5.4 h and OLR range of ~18–~44 g COD/L·h. Moreover, the addition of the tertiary MBR stage offered a further treatment opportunity, which was achieved by a removal amount of 99% for COD, TSS, and FOG. The resultant effluent exceeded the set standard for effluent discharge. The system can be recommended as an effective solution for voluminous bird slaughtering industries.

3.5. References

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CHAPTER FOUR

CONCLUSION AND RECOMMENDATIONS

Part of this chapter has been published in below extended abstract:

Dyosile, P.A., Basitere, M. & Ntwampe, S.K.O. 2019. “Poultry Slaughterhouse Wastewater Treatment Using a Down-Flow Expanded Granular Bed Reactor Coupled with Single Stage Nitrification-Denitrification System, Submerged Membrane, and Ultraviolet System”*. 12th Eastern European Young Water Professionals Conference*. 31 March -2 April 2021, Riga, Latvia. First Edition, Pp 126-127. ISBN: 978-9934-22-618-2.

CHAPTER FOUR

4. Conclusion and Recommendations

Subsequent to the increasing poultry products' demand, the generated large volume of high-strength poultry slaughterhouse wastewater, rich in organic compounds, nutrients and solids from the blood, urine, faecal matter and detergents has made treatment necessary for environmental protection and water sustainability. This thesis explored the designed technologies for successful treatment of poultry slaughterhouse wastewater: The benefits, deficiencies leading to the development of the down-flow expanded granular bed reactor and biological pre-treatment.

Furthermore, the study assessed the performance of an integrated multistage laboratory-scale plant, for the treatment of poultry slaughterhouse wastewater (PSW). The system was comprised of an eco-flush dosed bio-physico pre-treatment unit for fats, oil, and grease (FOG) hydrolysis prior to the PSW being fed to a down-flow expanded granular bed reactor (DEGBR), coupled to a membrane bioreactor (DEGBR-MBR). The system's configuration strategy was developed to achieve optimal PSW treatment by introducing the enzymatic pre-treatment unit for the lipid-rich influent (PSW) in order to treat FOG including odour-causing constituents such as H_2S known to sour anaerobic digestion (AD) such that the PSW pollutant load is alleviated prior to AD treatment. This was conducted to aid the reduction in clogging and sludge washout in the DEGBR-MBR systems and to achieve the optimum reactor and membrane system performance. A performance for the treatment of PSW after lipid reduction was conducted through a qualitative analysis by assessing the pre- and post-pre-treatment units' chemical oxygen demand (COD), total suspended solids (TSS), and FOG concentrations across all other units and, in particular, the membrane units. Furthermore, a similar set-up and operating conditions in a comparative study was also performed. The pre-treatment unit's biodelipidation abilities were characterised by a mean FOG removal of 80% and the TSS and COD removal reached 38 and 56%, respectively. The final acquired removal results on the DEGBR, at an OLR of ~18–45 g COD/L.d, was 87, 93, and 90% for COD, TSS, and FOG, respectively. The total removal efficiency across the pre-treatment-DEGBR-MBR units was 99% for COD, TSS, and FOG. Even at a high OLR, the pre-treatment-DEGBR-MBR train seemed a robust treatment strategy and achieved the effluent quality set requirements for effluent discharge in most countries.

Recommendation for future studies include operational costs of the research study to establish effective procedures at lowest cost to fit industrial goals, a study on other available membranes as additional option should submerged membranes use in this study prove to weaken over time from the chosen wastewater. Furthermore, a study on the qualitative and quantitative study on biogas production may be beneficial as biogas sales may generate money to support operational costs.

CHAPTER FIVE

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CHAPTER 5

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APPENDICES

APPENDICES

Appendix A: Analytical Methods

A.1. Total Chemical Oxygen demand Analysis

Apparatus

- Spectroquant thermoreactor
- Beaker 250ml
- Pipette (P5000 and P1000)
- Nova 60
- Cells
- Stopwatch

Procedure

- Spectroquant thermoreactor was set to preheat to 148 °C. During which, 100ml of distilled water was poured into a beaker.
- 2.2ml COD solution A and 1,8ml of COD solution B was drawn using a P5000 pipettes into separate cells.
- Using a clean pipette, 3ml sample of the PSW sample was added into each cell and vigorously mixed.
- Once mixed, by shaking, cells were placed in thermoreactor for 2 hours. After which, cells were placed on a test-tube rack to cool.
- When cooled, cells were placed into Nova60, ensuring the cell indicator line was in line with that of the Nova60, for results reading.

A.2. Total suspended solids Analysis

Apparatus

- Glass microfibre filter discs
- Disposal aluminium dishes
- Tweezers
- 1L Suction flask
- Glass microanalysis filter holder.
- Drying oven (103 to 105 °C).

- Furnace (550± 50 °C).
- Desiccator.
- Analytical balance.
- Milli-Q® reagent grade water (ASTM Type-1 water).

Procedure

- Filter disc was inserted on the funnel.
- While vacuum was applied, the filter paper was washing with 20ml of Milli-Q® reagent grade water (ASTM Type-1 water) thrice.
- Once the water was thoroughly suctioned, filter paper was placed on aluminium disc and into the furnace for 30 minutes.
- After which, filter was rewashed using the same process of 3 x 20ml Milli-Q® reagent grade water (ASTM Type-1 water)and dried in the drying oven at a temperature range of 103 – 105 °C for 60minutes and weighed.
- A 200ml sample was collected.
- The filter was secured on the funnel, using small squirts of the Milli-Q® reagent grade water under vacuum suctioning and the sample was transferred into the funnel through the filter with the vacuum applied to remove water.
- Using a pair of tweezers, the filter was removed from the base of the funnel and placed in the drying oven for approximately 60 minutes, at a temperature range 103 – 105 °C.
- The Filter was placed in desiccator to cool.
- When cool, the filter was weighed and using the wet and dry mass readings, TSS was calculated and per formula below.

Calculation for total suspended solids

$$\textbf{\textit{TSS (mg/L)}} = \frac{(\boldsymbol{W1}-\boldsymbol{W2})}{\boldsymbol{V}}$$

Where;

W1 = Weight of filter paper and dish + residue in (mg).

W2 = Weight of filter paper and dish (mg).

V = Volume of sample filtered (L).

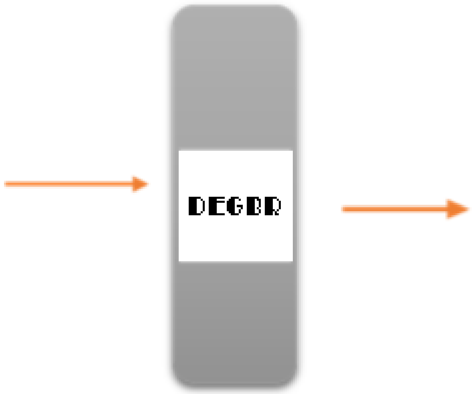
Appendix B: Formulae

$$HRT = \frac{V_{reactor}}{Q_{feed}}$$

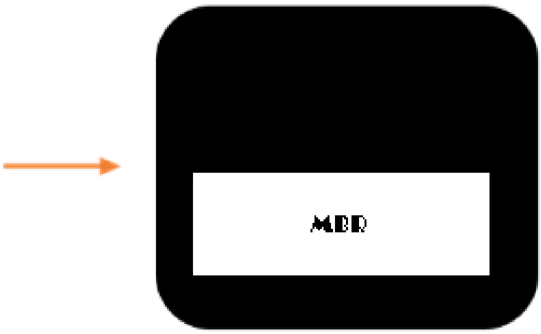
$$OLR = \frac{Q_{feed}COD_{feed}}{V_{reactor}}$$

$$Removal\ Percentage\ (\%) = \frac{Inlet\ value - Outlet\ value\ Inlet\ value}{nlet\ value}\ X\ 100$$

DEBR flow rates = 0,37 L/h



MBR flow rates = 0,38 L/h



Appendix C: Raw Data

Pre-treatment Raw Data									
TIME	**REMOVAL (%)**			**CONCENTRATION (mg/L)**					
Weeks	**COD**	**TSS**	**FOG**	**FOG_outlet**	**FOG_inlet**	**COD_outlet**	**COD_inlet**	**TSS_outlet**	**TSS_inlet**
7	27	63	67	320	980	4968,25	6800	1200	3200
14	28	53	71	230	780	4700	6500	1985	4200
21	33	55	84	210	1320	4968,25	7415	1450	3245
28	42	60	69	198	640	4968,25	8566	1180	2985
35	43	54	80	245	1230	6700	11754	2100	4580
42	50	48	75	370	1478	5645	11290	3345	6433
49	23	43	80	245	1200	8030	10429	3100	5395
56	35	74	85	265	1800	4975	7654	1173	4500
63	53	62	92	312	3840	9850	21000	3200	8363
70	33	49	87	320	2430	6450	9627	2650	5227
77	36	54	83	345	1980	4370	6828	2140	4650
84	44	55	80	298	1460	5130	9161	3120	6969
91	56	64	93	320	4500	6320	14364	2850	7964
98	42	57	85	265	1760	4670	8052	2460	5767
105	36	48	88	242	2100	4800	7500	2785	5395
112	29	57	81	210	1135	5320	7493	2145	4993

Pre-treatment Raw Data Cont.									
TIME	**REMOVAL (%)**			**CONCENTRATION (mg/L)**					
Weeks	**COD**	**TSS**	**FOG**	**FOG_outlet**	**FOG_inlet**	**COD_outlet**	**COD_inlet**	**TSS_outlet**	**TSS_inlet**
119	42	52	89	210	1940	7320	12621	2980	6194

DEGBR Raw Data									
TIME	**REMOVAL (%)**			**CONCENTRATION (mg/L)**					
Weeks	**COD_removal**	**TSS_removal**	**FOG_removal**	**FOG_inlet**	**FOG_outlet**	**COD_inlet**	**COD_outlet**	**TSS_outlet**	**TSS_inlet**
7	75,45	95,33	86,56	320	43	4200	1031	56	1200
14	61,62	97,08	88,26	230	27	4560	1750	58	1985
21	79,58	97,10	88,10	210	25	4800	980	42	1450
28	77,36	98,90	94,44	198	11	5300	1200	13	1180
35	85,52	95,81	89,39	245	26	6700	970	88	2100
42	79,20	79,07	91,35	370	32	5645	1174	700	3345
49	94,40	91,68	92,65	245	18	8030	450	258	3100
56	92,80	83,29	89,43	265	28	4975	358	196	1173
63	95,37	88,75	86,54	312	42	9850	456	360	3200
70	86,20	84,83	92,81	320	23	6450	890	402	2650

DEGBR Raw Data Cont.									
TIME	**REMOVAL (%)**			**CONCENTRATION (mg/L)**					
Weeks	**COD_removal**	**TSS_removal**	**FOG_removal**	**FOG_inlet**	**FOG_outlet**	**COD_inlet**	**COD_outlet**	**TSS_outlet**	**TSS_inlet**
77	95,42	97,38	92,17	345	27	4370	200	56	2140
84	89,08	94,81	95,97	298	12	5130	560	162	3120
91	88,88	92,98	90,00	320	32	6320	703	200	2850
98	92,29	92,20	86,04	265	37	4670	360	192	2460
105	95,21	93,39	82,64	242	42	4800	230	184	2785
112	93,61	95,34	86,19	210	29	5320	340	100	2145
119	96,64	94,90	87,62	210	26	7320	246	152	2980

DEGBR-MBR RAW DATA									
TIME	**REMOVAL (%)**			**CONCENTRATION (mg/L)**					
Weeks	**COD_removal**	**TSS_removal**	**FOG_removal**	**FOG_inlet**	**FOG_outlet**	**COD_inlet**	**COD_outlet**	**TSS_inlet**	**TSS_outlet**
7	89	97	75	43	11	1031	111	56	2
14	93	88	81	27	5	1750	125	58	7
21	85	64	25	25	19	980	147	42	15

DEGBR-MBR RAW DATA Cont.

TIME	REMOVAL (%)			CONCENTRATION (mg/L)					
Weeks	**COD_removal**	**TSS_removal**	**FOG_removal**	**FOG_inlet**	**FOG_outlet**	**COD_inlet**	**COD_outlet**	**TSS_inlet**	**TSS_outlet**
28	85	62	60	11	4	1200	180	13	5
35	80	93	58	26	11	970	192	88	6
42	87	93	58	32	13	1174	153	700	50
49	90	97	51	18	9	450	45	258	8
56	84	96	42	28	16	358	57	196	8
63	94	98	79	42	9	456	27	360	7
70	96	96	84	23	4	890	34	402	16
77	94	99	89	27	3	200	11	56	1
84	88	98	80	12	2	560	67	162	3
91	86	94	65	32	11	703	99	200	12
98	90	99	54	37	17	360	36	192	2
105	85	92	67	42	14	230	34	184	15
112	87	95	71	29	8	340	44	100	5
119	79	84	68	26	8	246	51	152	24

OVERALL SYSTEM DATA									
TIME	**REMOVAL (%)**			**CONCENTRATION (mg/L)**					
Weeks	**COD_removal**	**TSS_removal**	**FOG_removal**	**FOG_inlet**	**FOG_outlet**	**COD_inlet**	**COD_outlet**	**TSS_inlet**	**TSS_outlet**
7	98,36	99,95	98,90	980	11	6800	111	3200	2
14	98,08	99,83	99,33	780	5	6500	125	4200	7
21	98,02	99,54	98,58	1320	19	7415	147	3245	15
28	97,90	99,83	99,31	640	4	8566	180	2985	5
35	98,37	99,86	99,11	1230	11	11754	192	4580	6
42	98,65	99,22	99,09	1478	13	11290	153	6433	50
49	99,57	99,86	99,27	1200	9	10429	45	5395	8
56	99,25	99,83	99,10	1800	16	7654	57	4500	8
63	99,87	99,91	99,77	3840	9	21000	27	8363	7
70	99,64	99,69	99,85	2430	4	9627	34	5227	16
77	99,83	99,99	99,85	1980	3	6828	11	4650	1
84	99,27	99,95	99,84	1460	2	9161	67	6969	3
91	99,31	99,85	99,75	4500	11	14364	99	7964	12
98	99,55	99,97	99,04	1760	17	8052	36	5767	2
105	99,54	99,73	99,33	2100	14	7500	34	5395	15
112	99,42	99,89	99,26	1135	8	7493	44	4993	5
119	99,59	99,62	99,57	1940	8	12621	51	6194	24

DEGR ADDITIONAL DATA					
Weeks	**pH**	**Temperature (°C)**	**OLR (g COD/L·h)**	**TDS_inlet (mg/L)**	**TDS_outlet (mg/L)**
7	7,03	37,3	19	1006	1106
14	6,9	37,6	20	1078	884
21	6,6	37,3	21	916	834
28	6,73	37,4	24	950	870
35	6,59	37,6	30	1268	1132
42	6,6	37,6	25	1422	1098
49	6,87	37,9	36	1340	1268
56	6,64	37,6	22	1212	1096
63	6,81	37,4	44	1156	1132
70	6,78	37,8	29	1054	809
77	7,01	37,7	19	730	698
84	6,98	37,4	23	1226	1140
91	6,98	37,4	28	982	511
98	6,825	37,65	21	969	684,5
105	6,67	37,9	21	956	858
112	6,84	37,7	24	1137	956
119	7,02	37,8	33	888	633