WATER QUALITY CHARACTERIZATION PROCEDURES FOR POULTRY SLAUGHTERHOUSE TREATMENT SYSTEMS

By

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DECLARATION

I, **Nazaire Nsanzimana**, declare that the contents of this thesis represent my 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.

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ABSTRACT

Water scarcity necessitates wastewater treatment. Overall, slaughterhouses generate a large volume of wastewater with a wide range of organic matter. This wastewater is characterised by the presence of a high concentration of chemical oxygen demand (COD), total suspended solids (TSS), fats, oil, and grease (FOG), and proteins. This can be said also for poultry slaughterhouse wastewater (PSW). The PSW has been previously treated utilizing the Static Granular Bed Reactor (SGBR) and Expanded Granular Sludge-bed Bioreactor (EGSB) as sole treatment systems. Therefore, the performance evaluation of an integrated multistage lab-scale system for the treatment of PSW as investigated in the present study, is required. The system included an Eco-flush^{TM} dosed bio-physio pre-treatment unit for FOG hydrolysis before the PSW is anaerobically in EGSB and SGBR linked to membrane bioreactors. This was a new design concept, therefore, quality tools, i.e. capability indices (Cp, Cpk, Pp, and Ppk) were used to monitor the potential performance of such a multi-stage lab-scale plant. The current design indicated a comparable performance as compared to previous studies for the removal of alkalinity, COD, FOG, SS, and TDS. Results indicated an overall performance of the SGBR in terms of alkalinity, COD, FOG, SS, and TDS removal efficiency being 75%, 88%, 83%, 54% respectively. As CPIs are an option for evaluating performance efficacy, the individual units in the multistage process, and the whole integrated process have shown that they can perform to the point where Pp and Ppk is equivalent to unity, reducing some water quality parameters by upto 99% in some instances for individual units. Even though Cp and Cpk were less than 1 at one point in the process, it was demonstrated that such an approach produces high-quality treated PSW, meeting environmental disposal specifications.

Keywords

Capability indices (CPIs); Expanded granular sludge bed bioreactor (EGSB); Membrane bioreactor (MBR); Poultry slaughterhouse wastewater (PSW); Static granular bed reactor (SGBR).

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DEDICATION

To my mother ***Genevieve MUREBWAYIRE***

RESEARCH OUTPUTS

- Nazaire Nsanzimana, Seteno Karabo O. Ntwampe, Moses Basitere and Mncedisi T. Dewa. 2019. The capability of Anaerobic Bioreactors for a Poultry Slaughterhouse Wastewater Treatment. 16th SOUTH AFRICA Int'l Conference on Agricultural, Chemical, Biological & Environmental Sciences (ACBES-19) Nov. 18-19, 2019 Johannesburg (S.A.). pp 280-282, https://doi.org/10.17758/EARES8.EAP1119142.

- Nsanzimana N., Ntwampe S. K. O., Basitere M., Dewa M. T. 2020 Capability Analysis of a Multi-Stage Process Design in Poultry Slaughterhouse Wastewater Treatment System. 12th Eastern European Young Water Professionals Conference. 31 March -2 April 2021, Riga, Latvia. pp 170-171, Book-of-Abstracts-ISBN.pdf (iwa-ywp.digital)

LAYOUT OF THESIS

The thesis is divided into the following chapters:

Chapter 1: The scope of the research: This chapter offers a brief overview of the research and its background. This is followed by a hypothesis, research problem, research questions, and supporting investigative questions. The study assumptions and constraints are listed to elucidate overall research design and methodology. The chapter also includes significant research objectives.

Chapter 2: Literature review: With its appendix (Appendix A), titled Capability of Anaerobic Bioreactors for a Poultry Slaughterhouse Wastewater Treatment, this chapter provides the background and a holistic overview of PSW treatment systems including other information perceived to important for the subject matter of the thesis.

Chapter 3: In this chapter, written in a form of a publishable paper, evaluation of CPIs in the five stages of the process designed is listed in the form of results and discussion, including the methods used to generate the discussed results and lastly, a conclusion and recommendations are made.

The references section provides a list of bibliography used to support the research.

Appendices: This section contains auxiliary information that is deemed not mandatory for the thesis's body.

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LIST OF ABBREVIATIONS AND ACRONYMS

ABBREVIATIONS	ACRONYMS
AD	Anaerobic Digestion
BOD	Biological Oxygen Demand
COD	Chemical Oxygen Demand
CPIs	Capability Process Indices
DWAF	Department of Water Affairs and Forestry
EGSB	Expanded Granular Sludge Bed
EWQMS	Emanti Management's Water Quality Management System
EPA	Environmental Protection Agency
FAO	Food and Agriculture Organization
FOG	Fat, Oil and Grease
HRT	Hydraulic Retention Time
ISO	International Organization for Standardization
MPCAC	Multivariate Process Capability Analysis Control
OECD	Organization for Economic Co-operation and Development
OLR	Organic Loading Rate
PCIs	Process capability indices
PSW	Poultry Slaughterhouse Wastewater
PWT	Poultry Wastewater Treatment
SANS	South African National Standard
SBR	Sequential Batch Reactors
SGBR	Static Granular Bed Reactor
SPC	Statistical Process Control
SSND	Single Scale Nitrification DE nitrification
TN	Total Nitrogen
TP	Total Phosphorous
TDS	Total Dissolved Solid
TSS	Total Suspended Solids
TWW	Treated wastewater
UASB	Up-flow Anaerobic Sludge Blanket
VOP	Voice of process
VOC	Voice of the Customer

LIST OF SYMBOLS

Symbol	Description
MCpm	Multivariate capability index
Cp	The process variability comparative to the modified tolerance region
D	The process deviation from the target
n	Sample size
V	Number of characteristics (dimension)
α	Type I error (usually α =0.0027).
T	Target value
LSL	Lower specification limit
USL	Upper specification limit

LIST OF FORMULAS

Chemical formulae	**Name**
NH_3	Ammonia
NH_3-N	Ammonia nitrogen
NH_4+	Ammonium
NH_4-N	Ammonium nitrogen
NO_2-	Nitrite
NO_2-N	Nitrite nitrogen
NO_3-	Nitrate
NO_3-N	Nitrate nitrogen
PO_4-	Phosphate

LIST OF GLOSSARY

Term	Explanation
Aerobic	Requiring free oxygen to break down organic contaminants and other pollutants.
Anaerobic	Requiring an absence of free oxygen to break down organic contaminants and other pollutants.
Biochemical oxygen demand (BOD)	The amount of oxygen required for the biotic degradation of organic matter in bodies of water.
Capability index	The statistical tool used to assess whether the process can produce within the customer's specification limits.
Chemical oxygen demands (COD)	A measure of the capacity of water to consume oxygen during the decomposition of organic and inorganic matter.
Conductivity	An ability of water to conduct electricity due to the presence or absence of certain ions.
Expanded granular bed reactor (EGSB)	A reactor that is similar but modified of the UASB reactor due to its faster rate of upward-flow velocity.
Hydraulic retention time (HRT)	An interval of time that wastewater remains in the system for being treated.
Membrane bioreactor (MBR)	A combination of a membrane process (microfiltration or ultrafiltration) with a biological wastewater treatment process.
Multivariate	Involving two or more variable quantities.
Organic loading rate (OLR)	The parameter indicates the number of volatile solids to be fed into the digester each day.
Process performance	A measure of how a process runs and reflects the accomplishment of individual targets.
Quality	The degree of excellence of something
Statistical significance	Statistical tests are used to determine whether the null hypothesis can be either rejected or retained

Total dissolved solids (TDS)	Total of organic and inorganic substances contained in water or wastewater.
Total suspended solids (TSS)	Solids in water that can be trapped by a filter.
Turbidity	The quality of being thick with suspended matter.
Wastewater	Used water discharged from homes, business, industry, and agricultural facilities
Voice of Customer (VOC)	A term that state allowed variation limits, and it reflects in the process specifications,
Voice of the process (VOP)	A term used to state the actual variation in a process, and it reflects in the control limits.

CHAPTER ONE

CHAPTER 1: INTRODUCTION

1..1 General background

Although water resources and sanitation are key necessities of life, water scarcity is an issue in most developing countries such as South Africa (Muller *et* al., 2009). There are potable water challenges due to the growing demands on freshwater resources (Dollar *et* al., 2010). Therefore, better monitoring, assessment, and forecasting of water needs and wastewater treatment, can alleviate these challenges (Dollar *et* al., 2010). However, most process industries are concerned with output, without assessing the generation of waste and wastewater. Most wastewater generated in food processing, is used to achieve quality conformity, product safety, and sanitization requirements imposed on the production facility.

The fact that poultry meat production and consumption has increased globally and nationally, it is quite predictable that an increase in the number of slaughterhouse facilities will ensue, subsequently increasing the volume of slaughterhouse wastewater produced. In this regard, wastewater treatment would be a critical process as untreated or improperly treated wastewater may lead to some problems affecting the environment, both animal and human health (Edokpayi *et al*., 2017). In this regard, anaerobic treatment is a practical and useful process to treat such wastewater, and it is almost certainly assured of increased usage in the future due to its treatment efficacy for high strength wastewater (Lim and Kim, 2014). Anaerobic digestion is among well-established treatment technologies to deal with high-strength wastewater and high levels of solid matter (Hanif *et* al., 2017). Although anaerobic treatment possesses great advantages, it hardly produces effluents that comply with current discharge limits and standards (Bustillo-Lecompte and Mehrvar, 2017). The current degree of understanding of different anaerobic reactors process's abilities for the removal of BOD, TDS, COD, FOG, VFA, TSS, VSS, TN, PO_4-P, NH_4-N, NO_3-N, at varying HRT, and OLR, has been initiated (Rinquest *et al*., 2019). Therefore, suitable multi-unit systems for the reduction of all these parameters is required.

Given, the advantages of anaerobic wastewater treatment and regulatory monitoring improvement by authorities, it is also important to look at quality characterization procedures for wastewater treatment processes. Hence, process capability analyses are required.

1..2 Problem Statement

One of the environmental challenges faced by the poultry is the generation of PSW. Chow *et al.* (2020) has proven anaerobic digestion as an effective way to treat PSW, with numerous studies reporting only on single stage processes using bioreactors like EGSB, and SGBR (AD systems) not coupled with either a pre- or post-treatment units. Considering the sensitivity of the AD system, requirement of a pre-treatment stage is essential with a post treatment providing quality assurance of the treated wastewater (Poh *et al*., 2016). It is anticipated that a proposed multi-stage process, can provide better performance in terms of PSW treatment than single units. This is the focus of this study. Prior to implementing this type of design at a pilot scale, process unit capability must be assessed.

1..3 Hypothesis

The current study hypothesizes that bio-physico pre-treatment - (SGBR / EGSB) - MBR system is capable of PSW treatment**.**

1..4 Primary research question:

To what extent is the designed la-scale process, i.e. bio-physico pre-treatment - (EGSB / SGBR) – MBR, is capable of adequately treating a high strength PSW?

1..5 Aim and Objectives

1..5.1 Aim

The study aims to monitor the quality performance of a bio-physico pre-treatment - (EGSB / SGBR) – MBR system.

1..5.2 Objectives

The primary research objectives are listed as follow:

- ***Objective one***: To determine the performance of the removal efficiency in terms of COD, TSS, BOD, TDS, and alkalinity in each stage of the process.
- ***Objective two***: To compare this performance with that observed in bioreactors used in previous studies, for each stage.

- ***Objective three***: To analyse CPIs (Cp, Cpk, Pp, and Ppk) in multi-stages of process designed.
- ***Objective four:*** To scrutinise CPIs for overall process on side of EGSB and SGBR trains.

1..6 Significance of the research and expected outcomes

The significance of this research is embedded in the for a high performance PSW treatment plant for the reduction of COD, TSS, BOD, TDS, and alkalinity for use by the poultry industry and others which produce high strength wastewater. The primary outcome is a process that is capable of effectively treating PSW.

1..7 Delineation of the research

This study will only focus on:

- PSW treatment
- Water quality disposal standards of the Western Cape Province, South Africa
- COD, TSS, BOD, TDS, and alkalinity.

CHAPTER TWO

2 CHAPTER 2: OVERVIEW OF POULTRY SLAUGHTERHOUSE WASTEWATER TREATMENT SYSTEMS.

2..1 Introduction

Chapter two reviews previous studies that are relevant to quality characterization procedures of PSW, and different treatment methods. The frameworks of process capability analysis as a quality tool to monitor processes such as SGBR and EGSB coupled with either pre- or post-treatment are also discussed. A review of research related to water and wastewater characteristics including its treatment is highlighted.

2..2 Background to the water and wastewater in poultry slaughterhouse

About 70% of earth's crust is covered by water, albeit only 3% is fit for human consumption. Water scarcity and percentage availability are highlighted in Figure 2-1. Hence, there is a need for more efficient water treatment and management. The surveyed literature indicates that water and wastewater management in South Africa is almost reaching a crisis level.

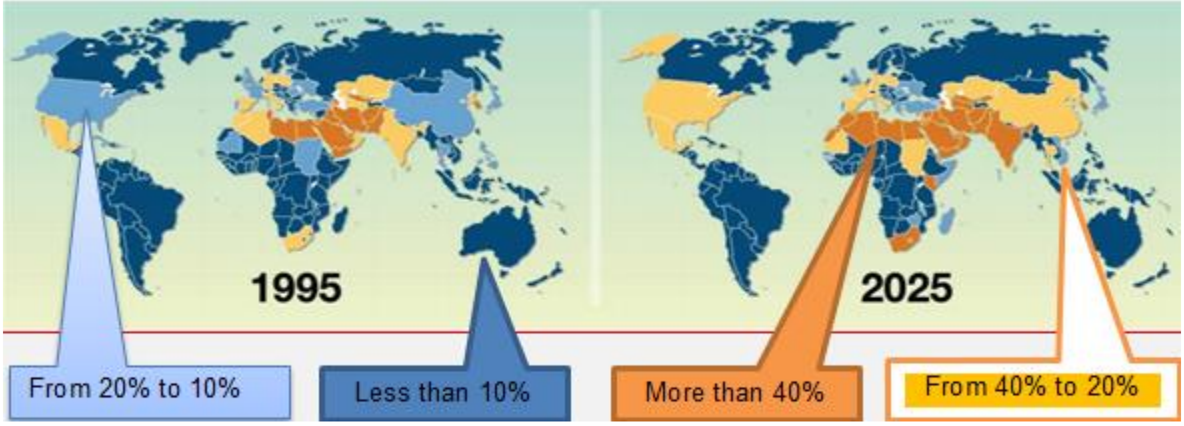

Figure 2-1: Water scarcity and percentage availability overview for 1995 - 2025 (Ran, 2010).

Current challenges are associated with water intake, sewage production, and the treatment of industrial wastewater. Within the food industries, meat production dominates in water consumption as shown in Figure 2.2. Therefore wastewater treatment in such industries is of paramount interest both in developing and developed countries (Matsumura and Mierzwa, 2008)

Overall, the poultry product industry generates a high amount of wastewater, from the consumption of potable water (Basitere et al., 2017a), thus the research interest in the treatment of slaughterhouse waste water (Valta et al., 2015).

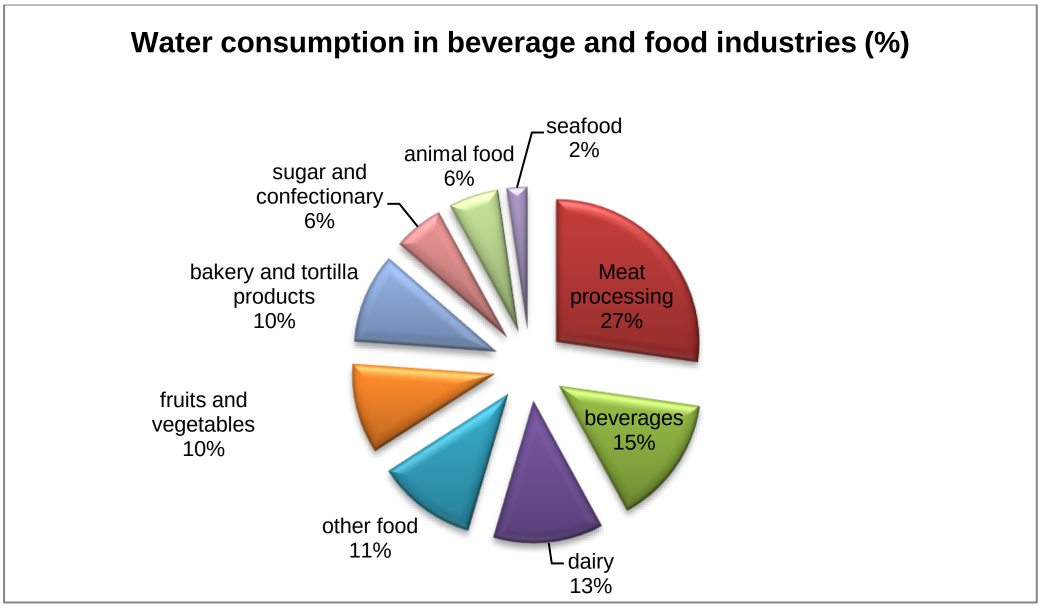

Figure 2-2: Typical water consumption in different industries (Valta *et* al. 2013)

The South African poultry industry also remains the largest single contributor to the agricultural sector, and its increase is evident on the continent, particularly considering countries in the region such as Botswana, Namibia, and Zambia (Bagopi et al., 2014). Therefore, the South Africa's poultry industry is one of the significant users of high-quality water too, which subsequently result in the generation of a high quantity of PSW.

2..3 Wastewater treatment approaches in poultry slaughterhouses

Generally, wastewater can broadly be defined as the used water from different users (homes, businesses, industries, commercial activities, and institutions) directed to wastewater treatment plants. The content of slaughterhouse wastewater depends on the industrial process and water demand used in processing products (Bustillo-Lecompte and Mehrvar, 2015). Aziz et al. (2019b) claimed that the slaughterhouse industry generates a considerable amount of wastewater rich in proteins, lipids, fibers, and carbohydrates. Similarly, Rajakumar et al. (2011) mentioned that wastewater discharged by poultry product producers is among the most polluted in the slaughterhouse industries, as it has a high biochemical oxygen demand, high-suspended solids, and a complex mixture of fats, proteins, and fibres. Figure 2-3 illustrates a brief classification of processes for the treatment of such wastewater with different units' treatments as:

- ✓ Preliminary and/or primary treatments using physical operations to remove suspended solids, fats, oil, and grease.
- ✓ Secondary treatments which are mostly biological to remove organic matter (COD, BOD, pathogens).
- ✓ Tertiary treatments, which can be chemical, biological and physical processes to further remove residual fats, suspended solids and nutrients.

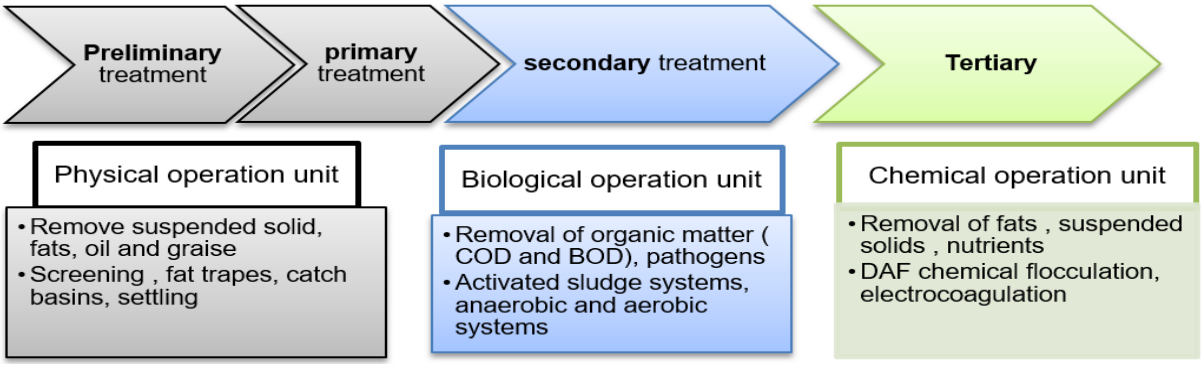

Figure 2-3: A brief classification and methods of the wastewater treatment process.

2..4 Biological wastewater treatment

Biological wastewater treatment refers to the microbial treatment of wastewater. According to the literature, there are several types, i.e. anaerobic, aerobic, and a combination of both anaerobic and aerobic digestions (Ashrafi *et a*l., 2015). The anaerobic bioreactor has been used widely in wastewater treatment plants due to its performance, and efficiency. AD performance happens in stages such as hydrolysis, acidogenesis, acetogenesis, and methanogens for the degradation of organic matter. These stages are shown in Figure 2-4.

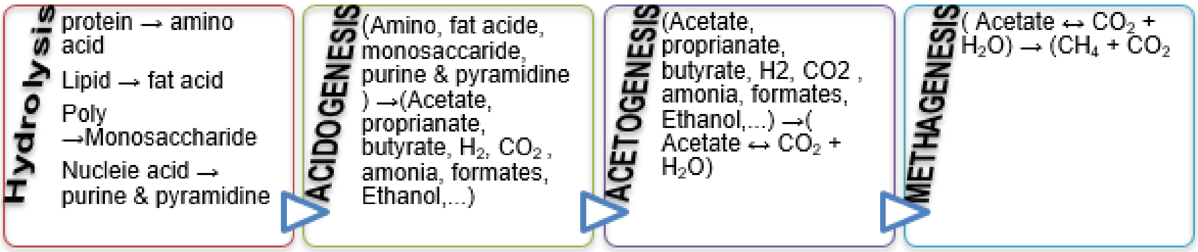

Figure 2-4: Four stages of anaerobic digestion process (Aziz *et al*., 2019).

There are some quantitative evaluations of the anaerobic digestion performance, i.e. its ability to remove biochemical oxygen demand (BOD), chemical oxygen demand (COD), and nitrogen. Some digester design considerations include hydraulic retention time, organic loading rate, total suspended solids, and operational temperature. Similarly, pre-treatments processes can be either biological, chemical, mechanical, thermal, or enzymatic (Mir *et al*., 2016). Rajab *et* al. (2017) investigated the performance of a new configuration laboratory-scale bioreactor comprising of anaerobic and aerobic systems, there is a balance between the broiler chicken producers' requirements such as a need for cheap, efficient, flexible, small footprint, less maintenance, and less sludge disposal systems due regulations that are imposed by the environmental protection agencies.

2..5 Anaerobic digesters

AD has been extensively hybridized, even though it is a biological technique that has been used to treat wastewater for decades. There have been various hybrids proposed, as shown in the list below by Meegoda et al (2018), with varying degrees of efficacy. Here is the partial list that typifies anaerobic digesters:

- Anaerobic activated sludge process
- Anaerobic digester
- Anaerobic contact process
- Anaerobic expanded-bed reactor
- Anaerobic filter
- Anaerobic fluidized bed
- Anaerobic lagoon
- Anaerobic MBRs
- Anaerobic migrating blanket reactor
- Batch system anaerobic digester
- Continuous stirred-tank reactor (CSTR)
- Expanded granular sludge bed digestion (EGSB)

- Hybrid reactor
- Internal circulation reactor (IC)
- Plug-flow anaerobic digester
- Submerged media anaerobic reactor
- Sintex Digester
- Two-stage anaerobic digester
- Up-flow anaerobic sludge blanket digestion (UASB)
- Up-flow and down-flow anaerobic attached growth

Overall, they are comparative studies on different AD reactors such as the Anaerobic Sludge Blanket (UASB), Expended Granule Sludge Blanket (EGSB), and Static Granular Bed Reactor (SGBR). IOWA State University's SGBR performed well with the COD removal efficiency of 90.7%, whereas that in the UASB reactor was 77.5%. Similar performances were observed for the UASB and EGSB (Lim and Kim, 2014). These types of bioreactor can be used for PSW treatment. However, the sludge morphology can influence the performance of such systems. Debik and Coskun (2009), evaluated the effectiveness between anaerobic sludge and anaerobic granule for PSW treatment, with granules having a lesser propensity to washout from the systems.

Del Nery *et al*. (2016) assessed a PSW treatment using AD with Wang and Yin (2017) using aerobic digestion t activated sludge consumed PSW organic matter in the presence of oxygen and convert it into carbon dioxide. However, AD was found to be an effective way to treat PSW. Nonetheless, the sensitivity of the AD system proves to be a challenge in ensuring consistent quality of treated wastewater (Poh *et al*., 2016). Hence, it is quite predictable that an intended new design consisting of a pre-treatment unit coupled with either EGSB or SGBR, including a MBR will need better-quality monitoring.

2..6 Aerobic-anaerobic systems

A major advantage of the use of combined anaerobic-aerobic processes is to reduce operating costs, compared to aerobic treatment alone. Combining both anaerobic and aerobic processes can improve resource recovery. By contrast, others report that the anaerobic systems results in very high overall treatment efficiency (Bustillo-Lecompte et al., 2013). The main disadvantage of combining aerobic and anaerobic treatment method is that additional treatment of phosphorus, is probably necessary (Bernet and Béline, 2009). One of the more practical ways of enhancing digestion, is to add a pre-digestion, enzymes, and bio-surfactants step (Harris and McCabe, 2015), albeit a tertiary step might be needed.

A well-known study by Basitere *et al* (2017), exemplified an assessment of the treatment efficiency of lab-scale SGBR anaerobic digester coupled with an UF membrane for COD removal to comply with the City of Cape Town regulations for industrial wastewater discharge standards. In the study, the bench-scale SGBR-UF membranes system was found to be a successful technique to treat PSW with COD, TSS, and FOG removal of 98.7%, 99.8%, and 92.24% respectively. Considering high concentrations of organic matter, nitrogen, and phosphorus that characterize PSW, biological pre-treatment is crucial (De Nardi *et* al., 2008). Previous research findings into biological pre-treatment of PSW raised issues like the high cost of organic coagulants, higher maintenance cost for operating a DAF, overdosing potential issue due to limited alkalinity, and excess phosphate in the wastewater (Dassey and Theegala, 2012). By then having such a pre-treatment system, the choice of a secondary AD process becomes simplified. For example, EGSB design plays a vital role for low strength soluble wastewaters (less than 1 to 2 g soluble COD/L) or for wastewaters that contain inert or poorly biodegradable suspended particles which should not be allowed to accumulate in the sludge bed (Saleh and Mahmood, 2003). According to Lim and Kim (2014), both EGSB, and SGBR have excellent performance in treating both low and high-strength wastewater. This means, the EGSB or SGBR can be coupled with a type of pre-treatment or post-treatment systems. Hence, the current study has to monitor the process design ‘s potential or capability.

2..7 Wastewater and water quality standards

The regulatory framework on effluent quality must be clear. To track, review and assess the water/wastewater quality, Emanti Management's Water Quality Management System (eWQMS) can be used. The following microbiological, physical, and some of the listed chemical parameters can be tested, i.e. Ammonia, Chemical Oxygen Demand, Electrical Conductivity, Faecal Coliforms, Free Chlorine Residual, Nitrates and Nitrites, Phosphates/Phosphorous, pH, Sodium Adsorption Ratio, Suspended Solids, and Total Kjeldahl Nitrogen.

Internationally, guidelines for wastewater must comply with the Environmental Protection Agency (EPA) standards. There is also an ISO 20419:2018 that outlines TWW parameters at the irrigation system inlet after a wastewater treatment plant, to allow optimal and continual functioning of the irrigation systems and to allow uniformity of emitters' discharge. Locally, DWAF set and regulate permits/licenses requirements for the quality of wastewater that can be discharged into the natural environment SANAS (South African National Accreditation System) focusing on accredited methods for sample analysis.

2..8 Wastewater quality compliance in the Western Cape and process control strategies to meet compliance standards

The compliance level: albeit outdated, with regard to wastewater discharge standards in the Western Cape, South Africa is reviewed and presented in Figure 2.5. The general average compliance was found to be 71%. Furthermore, Kostyla et al. (2015) critics global wastewater-quality management and compliance, opining that there is largely non-compliance due to the increasing population and developing economies whereby monitoring is lacking. Therefore, the research of the related barriers and the relevant mitigation approaches to detect obstacles associated with non-compliance is needed (Huang and Xia, 2001).

As a methodology, Amsden (2019) classifies statistical process control (SPC) to measure the performance of a process. As such, rudimentary treatment plants can be assessed using such an approach in order to control the wastewater processes, but this is largely not done. Although, an increase of environmental control needs advanced processes monitoring and performance techniques of a process or a plant, the implementation of such can be achieved. Khudair and Jasim (2018) designated non-linear MSPC technique to overcome the better performance for biological wastewater treatment.

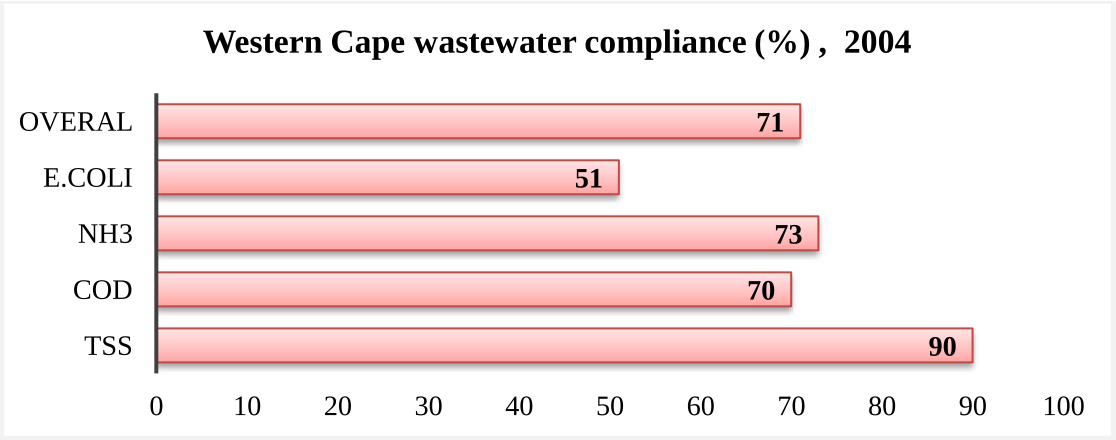

Figure 2-5: Western Cape wastewater compliance in 2004.

Figure 2-6 defines the quality of wastewater by characterizing the main parameters, which support the choice of quality parameters of the current study and which can be used to monitor the processes. Tomar and Kaur (2019) elaborated these quality characteristics as physical characteristics: the physical state of water that associate with the sense of touch, taste, sight or smell, color, temperature, taste, odor, turbidity, conductivity, and suspended solids. Biological characteristics are non-pathogenic and pathogenic microbes, and oxygen demand created by the ecosystem present in water and wastewater. Chemical characteristics will include alkalinity, acidity, hardness, metallic and non-metallic, biodegradable, and non-biodegradable organics, and nutrients (are parameters of concern in water and wastewater quality management). All these can be monitored and controlled in a wastewater treatment plant which uses effective SPC.

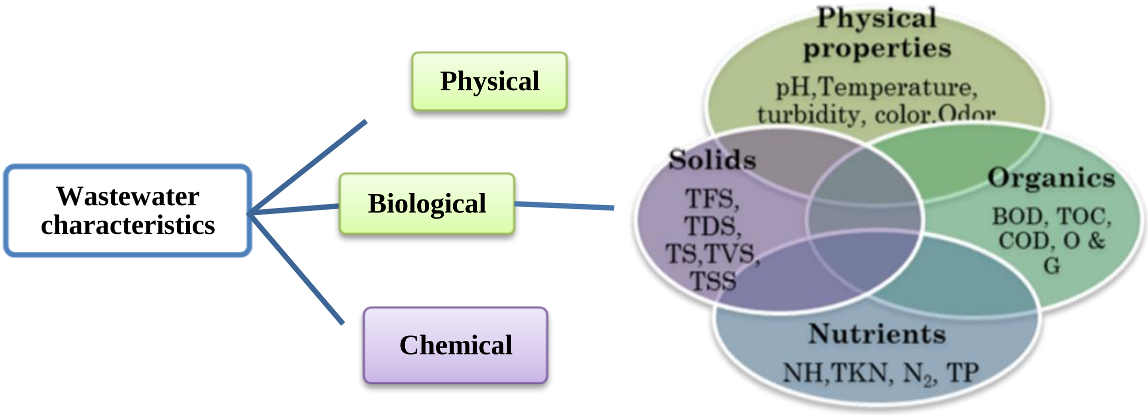

Figure 2-6: Schematic diagram of main quality parameters of wastewater.

2..9 Poultry slaughterhouse wastewater quality standards

There have been several investigations into PSW quality characteristics, and Raja Kumar *et al.* (2011) characterized the wastewater discharged by poultry slaughterhouse industries not comply with disposal standards. Yaakov *et al*. (2018) examined chicken slaughterhouse wastewater and came up with a typical characterisation of such wastewater, which is illustrated in Table 2-1. As observed these parameters are out of the Environmental Quality Act, 1974 (EQA 1974) range.

Table 2-1: Characteristic of chicken slaughterhouse wastewater Adopted from Yaakob *et* al., (2018).

	Study one			Bustillo-Lecompton *et*.al (2016)		EQA1974	
Parameters	min	max	mean	max	mean	Standard A	Standard B
pH	7.3	8.6	8.02	4.9	8.1	6.0 -8.10	5.5 - 9.0
BOD	1341	1821	1602	610	4635	20	50
COD	3154	7719	5422.3	1250	15900	50	100
TSS	378.7	5462	3438.2	300	2800	50	100
TN	162.6	564	361.25	50	841	NR	NR
TOC	194.9	652	419.3	100	1200	NR	NR
PO43-	7.047	17.1	12.256	NR	NR	NR	NR
F	0.221	0.64	0.493	NR	NR	NR	NR
NO3	1.643	3.27	2.241	NR	NR	NR	NR

NR: *Not Reported*

Similarly, the characteristics of PSW in the Western Cape were also reported elsewhere (Basitere *et* al., 2017) – see Table 2.2.

Table 2-2 : Characteristics of the PSW in the Western Cape (source: Basitere *et* al., 2017).

parameter (mg/L)	**min**	**max**	**Average**
BOD	610	4635	1209
Ca	32	316	67
COD	1250	15900	4221
K	0.01	100	90
Na	62	833	621
Pb	0.21	34	4
TN	50	841	427
TOC	100	1200	546
TP	25	200	50
TSS	300	2800	1164
pH (no unit)	4.9	8.1	6.95

CHAPTER THREE

3 CHAPTER 3: CAPABILITY ANALYSIS OF A MULTI-STAGE PROCESS DESIGNED FOR POULTRY SLAUGHTERHOUSE WASTEWATER TREATMENT: A FOCUS ON FATS-OIL-GREASE, AND ALKALINITY REMOVAL

Capability Analysis of a Multi-Stage Process Designed for Poultry Slaughterhouse Wastewater Treatment: A Focus on Fats-Oil-Grease, and Alkalinity Removal

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3..1 Abstract

Wastewater treatment is crucial in addressing water shortages; however, slaughterhouses create a significant amount of wastewater with a wide range of organic matter concentrations. Several research using the Static Granular Bed Reactor (SGBR) and Expanded Granular Sludge-bed Bioreactor (EGSB) in slaughterhouse wastewater treatment looked at the treatment of poultry slaughterhouse wastewater (PSW). Thus, a multi-stage lab-scale plant was employed in this investigation, which included a pre-treatment stage, two trains with either an SGBR or EGSB coupled individually to membrane bioreactors (MBRs). The lab-scale plant was run for 11 weeks, and capability indices (Cp, Cpk, Pp, and Ppk) were applied. The experimental data was examined using QI Macros as one of statistical process control software which has outstanding value.

The lab-scale plant with three phases, i.e. bio-physical pre-treatment stage – SGBR or EGSB units – MBRs and in stage 1. Eco-flush^{TM} has been used to improve water quality parameters for the current study which are comparable with others reported in Table 3.1. Looking at existing study on biological Pre-treatment coupled with the down-flow expanded granular bed reactor (DEGBR) , and for treatment of PSW results agree well with different studies of the same scale-plant design. This argument of the potential of the process is consistent with the list of findings of the overall removal efficiency performance of pre-treatment coupled with DEGBR in terms FOG, COD, and TSS, was 97 ± 0.8%, 92 ± 6.3%, and 97 ± 1.2% respectively (Dlamini et al., 2021), again the potential of process observation agrees with the system (pre-treatment–EGSB–MBR) exceeded 97% for TSS and COD removal and 97.5% for FOG removal, which was similar to that investigated in the study of (Meyo et al., 2021). Furthermore, Phumeza et al., (2021) assessed the performance of an integrated multistage lab-scale plant and found 87%, 93%, and 90% for COD, TSS, and FOG, respectively.

As a result, in light of the abilities described in these many research, it is reasonable to conclude that the current study has produced novel contributions in multiple areas, such as additional analysis. Overall performance of process coupled with SGBR, for alkalinity, COD, FOG, SS, and TDS removal efficiency of 75 %, 88 %, 4 % 83 %, and 54 %, respectively, was reached in the current study. In addition, the CPIs approach is a promising alternative to analyze the designed process, which has shown that its approach can perform to the point where Pp and Ppk equal 1, It also indicates that 99.73 % of the system's output fits specifications. Although Cp and Cpk at one stage of the process were less than 1, it was proven that such an approach produces high-quality outputs, with over 75% of the output from all phases of the process satisfying the specifications.

Keywords

Capability indices (CPIs); Eco-flush, expanded granular sludge bed bioreactor (EGSB); Membrane bioreactor (MBR); poultry slaughterhouse wastewater (PSW); static granular bed reactor (SGBR).

3..2 Introduction

Globally, slaughterhouses generate high-strength wastewater from both the slaughter line and viscera, with a large variation in the concentration of organic matter, which is the main pollutant in slaughterhouse discharges (Farzadkia et al., 2016). There has been a renewed interest in the existing literature focusing on poultry slaughterhouses that generate significant volumes of wastewater, i.e. poultry slaughterhouse wastewater herein referred to as PSW (Aziz et al., 2019a). It is also known that PSW can be treated successfully at a very low cost using anaerobic wastewater treatment systems (Debik and Coskun, 2009). The quality thus the strength of PSW, is measured by the content of its organics, nutrients, and solids (Muttamara, 1996). A review has been done to understand the treatment systems related to PSW treatment and their efficiency, whereby wastewater discharge standards and regulations, and applicable technologies are highlighted, in particular, for nutrient and organic matter removal for such wastewater during the last 10 years (Baker et al., 2020). Additionally, according to Loganath and Senophiyah-Mary (2020), 270 pieces of literature were collected and documented to characterize the waste and wastewater from slaughterhouses, including treatment efficiency of various anaerobic bioreactors used, identifying crucial and/or influential parameters that affect the overall wastewater treatment processes involved, i.e. anaerobic digestion.

Del Nery et al. (2007), evaluated the performance and process stability of a full-scale PSW treatment plant by removing organic matter over 4 years, revealing that the Up-flow anaerobic sludge blanket (UASB) reactors were potentially suitable to maintain satisfactory performance in face of a future planned chicken meat production growth in the industry. A shortcoming of this analysis is that the organic matter and the nutrients concentrations in the treated effluent needed further post-treatment. Similarly, Static Granular Bed Reactor (SGBR) and Expanded Granular Sludge-bed Bioreactor (EGSB) systems were determined to be one of the most widely used bioreactors for wastewater treatment, including the treatment of different types of wastewaters including PSW (Basitere et al., 2017b); albeit both the EGSB and SGBR have been analyzed independently, there is further analysis required for these systems' integration with other wastewater treatment stages, i.e. bio-physical pre-treatment and tertiary stages such as membrane bioreactor systems (MBRs). This can be achieved using an integrated capability analysis, even for the treatment of PSW.

Capability analysis has been mostly applied in the fast-moving consumer goods industries for process intensification and improvement while identifying some key factors in such manufacturing (Wooluru et al., 2014). Process capability and performance indicators or indices (Cp, Cpk, Pp, and Ppk), are currently well-known process quality tools, for both the estimation of process efficiency and can thus be used to monitor and determine any process capability (Chan et al., 1988). Process capability indices have been used in different industries to quantitatively measure process performance and are hardly ever used in wastewater treatment. However, others have reviewed and reported on process capability indices (PCI) such as Cp, Cpk, Pp, and Ppk and successfully implemented these indices to measure process quality and performance (Huang and Chen, 2003). The monitoring of processes can often involve a multistep process, with process monitoring techniques such as Hotelling's T^2, multivariate cumulative sum control chart (CUSUM), and exponentially weighted moving average (EWMA) charts, being mostly used. However, all these techniques are intended for a single-stage process because they cannot effectively identify the stage with the root cause in a multistage process. Fortunately, the multistage processes can be monitored by charting individual process stages process separately (Tsung et al., 2008). To overcome such a challenge, process capability indices have been used in different industries to quantitatively measure an integrated process performance (Aslam et al., 2019). In multi-stage processes, the total process capacity index and unique process capacity index can also be described at each process stage even in multi-stage processes (Sarkar, 2019). Experts of industrial statistics are usually familiar with and apply the common Cp and Cpk process capability indices.

Hence, these methods were preferred to measure the performance of a designed lab-scale plant for PSW treatment. Therefore, this study reports on the process capability of a multi-stage lab-scale plant which consisted of a bio-physical pre-treatment stage, two trains with either an SGBR or EGSB coupled individually to membrane bioreactors (MBRs). Therefore, process capability indices were applied to the designed wastewater treatment process illustrated in Figure 1, using secondary experimental data and QI Macros 2021 (SPC software for Microsoft Excel). Overall, the process designed for the current study demonstrated the development, efficacy, and applicability of the bio-physical pre-treatment stage - SGBR/EGSB anaerobic units – MBR systems for PSW treatment. This technology can be applied by poultry slaughterhouses globally in particular for Fats-Oil-Grease (FOG), and alkalinity removal.

3..3 Materials and Methods

Two anaerobic reactors, i.e. EGSB and SGBR, were designed in such a way that both were coupled to both a bio-physical pre-treatment and post-treatment (MBR) stages to remove alkalinity, Chemical Oxygen Demand (COD), FOG, Suspended Solids (SS), and Total Dissolved Solids (TDS) – all of which are key parameters in wastewater treatment. Subsequence subsections deliberate briefly on capability analyses and interpretation, i.e. parameters for the lab-scale plant design, data collection, and analyses.

3..3.1 Assumptions

To make a process capability analysis successful in either the long or short term, the following assumptions were applied in this study: *in control*, and *stable*.

3..3.2 Capability analyses and interpretation

The reason for using capability analyses is such that each stage's influence on the overall process can be evaluated (Wooluru et al., 2014). Overall, a process capability study is carried out to measure the ability of a process to meet defined specifications. A key aspect of process capability indices Cp and Cpk is such that they are used for process capability analyses and to measure the ability of a process to meet predetermined or suitable specifications – see Equation (1) which explains Cp, i.e. what a process can do under certain defined conditions (the spread of variation present in a process).

$$\mathbf{Cp} = \frac{\text{Allowable process spread (Design tolerance)}}{\text{Actual process spread(6Sigma)}} \qquad \textbf{Equation 1}$$

While Equation (2) shows a Cpk that measures the actual capability or an estimation of the capability of what the process is doing over an extended time (performance capability of the process).

$$\mathbf{Cpk} = \text{minimum between } \frac{\text{USL}-\mu}{3\text{ Sigma}} \text{ and } \frac{\mu-\text{LSL}}{3\text{ Sigma}} \qquad \textbf{Equation 2}$$

Where *USL: Upper specification limit*, *LSL: Lower specification limit*, and *μ:* Target

3..3.3 Interpretation of capability index

A possible value of the Cp value should be ≥ 1.33 during the normal performance of a process. Notwithstanding that the Cpk would be equivalent to Cp when the average of the performance specification is the same as the target value, with the Cpk value always being less or equivalent to Cp. Normally, if a CPI is less than 1.00; it indicates that the process is inadequate to fulfill process tolerances and performance specifications, with either the process variations needing to be reduced or the process needing a correction to be closer to the performance target value. Otherwise, a process is capable of its designed purpose when 1.00 ≤ CPI ≤1.33 (Pearn and Kotz, 2006). Process performance requirements are normally set by users of the technology; hence in the current study, CPIs standards were compared to some technologies from previous similar studies.

3..3.4 Quality parameters of the PSW used

Some quality parameters defining the characteristics of the wastewater from an industrial poultry slaughterhouse in the Western Cape, South Africa were reported elsewhere (Basitere et al., 2016), and these were used to monitor the performance of the treatment units (stages) and the whole process designed for PSW treatment. Some typical key parameters to be monitored and their values including regulatory standards are highlighted in Table 3-1.

Table 3-1: Some reviewed characteristics of the PSW within different standards.

Parameter (mg/L)	**Method ISO (Noukelag et al., 2021)**		**Average ± SD (Rajab et al., 2017)**	**CCT by-law limit**	**SANS 241: 2011**	**Average of in and effluents for the current study**
COD	M2	ISO 6060**	2711 ± 487	5000	488	1895 - 3009
FOG	-	ISO 11349	281 ± 63	400	-	97 - 224
Alkalinity	-	ISO 6107-2	160 ± 21	-	2447	685 - 762
TSS	M8	ISO 11923	835 ± 162	4000	24	297 - 730
TDS	-	-	917 ± 135	1000	280	1043 - 1190

3..3.5 Lab-scale plant design

From a quality perspective, a multi-stage (stage1-3) and multi-response system (from quality parameters), is dependent on input factors that can be used to predict immediate responses for individual stages. These response factors can then be the input factors for the subsequent stages (Beshah et al., 2015). **Figure 3-1** portrays the individual units assessed for the laboratory-scale PSW treatment system designed.

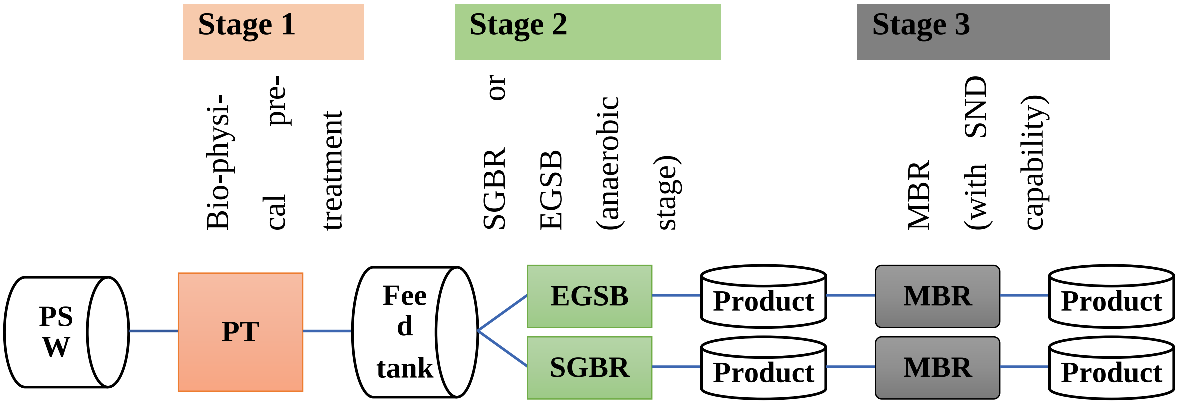
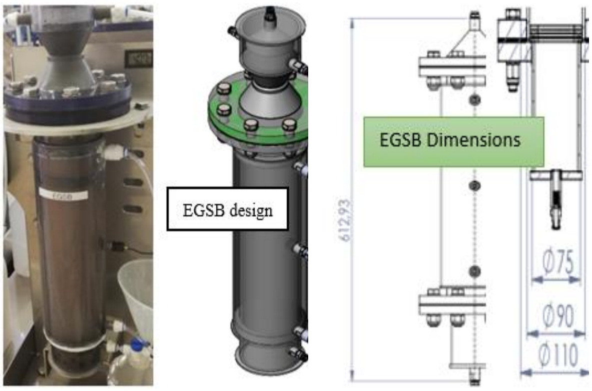


Figure 3-1 : Illustrated targeted design of multi-variate and stage process for a pilot PSW treatment plant. SND simultaneous nitrification and aerobic denitrification.

Stage 1: The PSW treatment system consisted of a biological pre-treatment stage whereby raw PSW was mixed with Eco-Flush^{TM} (0.1% v/v) which is a commercial product solution produced by Ergofito Pty Ltd and sourced from Mavu Biotechnologies (Pty) Ltd as an assemblage of consortia able to produce hydrolases. The microorganisms therein are organisms that had been isolated from the soil, grown, and stored in a physiologically dormant state, and can be subsequently invigorated in a carbon source-rich environment. The Eco-Flush^{TM} was used in this study for PSW biological delipidation, i.e. FOG hydrolysis, before the hydrolyzed PSW entered a holding tank from which the FOG hydrolyzed PSW is fed to both the EGSB and SGBR independently. Preliminary contaminant removal, i.e. removal of organic matter and other pollutants in the PSW, ensued at this stage, using a set-up as shown in **Figure 3-2**. As defined by ISO 9000:2005, a process is a sequence of activities that are interconnected or communicate with one another to turn inputs into outputs (Domittner et al., 2013); hence, this first stage (raw PSW pre-treatment) was expected to reduce the amount of alkalinity, COD, FOG, SS, TDS that were into the PSW tank to some extent.

Figure 3-2 : Photograph of the raw PSW container and a mixture of Eco flush in aerating process. (Image by Nsanzimana N.)

Stage 2: The EGSB and SGBR were made from a cylindrical polyvinyl chloride (PVC) material with a cylindrical column, both having 2L operating volumes. The height of the EGSB was 61.293 cm with an internal diameter of 9 cm and 11cm for external diameter, while the height was 62.8 cm with an internal diameter of 9 cm and an external diameter of 11cm for the SGBR. Moreover, ceramic marbles (diameter of 8.14 cm) were packed at the bottom of each reactor as an underdrain for sludge retainment. Both reactors are illustrated in **Figure 3-3** and **Figure 3-4**. PSW was fed into the EGSB and SGBR through peristaltic pumps from the bottom (EGSB) and top (SGBR), respectively. The products from the EGSB and SGBR reactors were sampled and stored in sterile polypropylene plastic bottles for the experiment before analyses. The second stage (SGBR and EGSB), was also designed to further reduce the amount of alkalinity, COD, FOG, SS, TDS that were from the pre-treatment stage (stage 1) via anaerobic digestion. These systems were operated as anaerobic digesters under predetermined conditions, i.e. hydraulic retention time (HRT) and temperature.



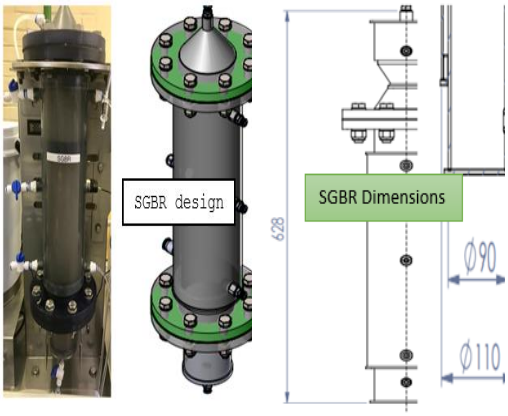


Figure 3-3 : EGSB design.

Figure 3-4 : SGBR design.

Stage 3: For this stage, MBRs were used, whereby a rectangular container (working volume of 120.51 L – see **Figure 3-5**) in which the membranes were immersed. The MBRs used were NADIR® UP150 membranes. These membranes are made of a permanently hydrophilic poly-ether-sulfone (PES) layer with a nominal pore size with a nominal molecular weight cut-off (M.W.C.O.) of 150,000 Daltons, and they were used in a dead-end filtration mode within a polyvinyl chloride (PVC) housing material. A mesh was around the membranes in the MBR unit to cover the membranes to minimize membrane clogging. Like the other stages, a further reduction of alkalinity, COD, FOG, SS, and TDS was the desired outcome.

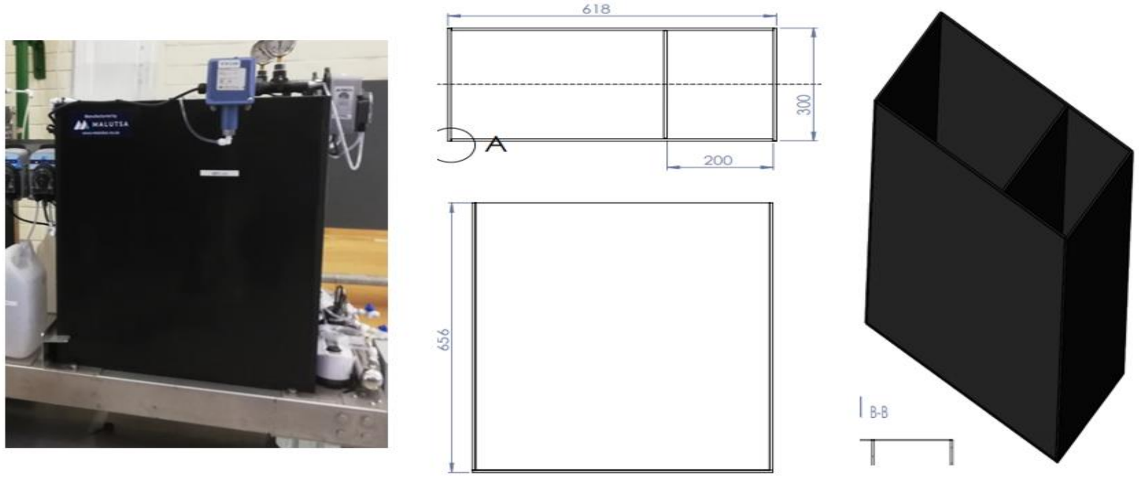


Figure 3-5: Rectangular container in which the membrane unit was immersed and its dimensions.

3..3.6 System preparation/operation and sample collection for wastewater analyses

For the pre-treatment stage operated in a fed-batch mode, the mixture of Eco-Flush^{TM} and PSW was aerated for 24 h at room temperature with air stone spargers to stimulate the microbial population in the Eco-Flush^{TM} supplemented PSW pre-treatment tank. The air sparging in the pre-treatment tanks for the PSW feed to be supplied to the EGSB and SGBR was thereafter switched off, with aggregated FOG and suspended solids being removed via screens.

The raw PSW used in this experiment was sampled using sterile 25L x 12 polystyrene containers once every two to three months, from a poultry slaughterhouse facility located in the Western Cape, South Africa. Then this raw PSW was kept in a refrigerator whose temperature was maintained below 4 °C to avoid its acidification (Njoya, 2019). Furthermore, several 15 L polystyrene containers of inoculum [activated sludge (AS)] were collected from a UASB operated for the treatment of brewery wastewater at a local brewery, SABMiller, Newlands, Cape Town.

The AS was then stored at 37 °C before being used to inoculate both the EGSB and SGBR bioreactors, with the inoculation procedure being completed by first putting the underdrain, then adding 0.4 L of AS to the individual reactors; with 1.6 L of raw PSW being added thereafter. Before AS addition to the reactors, Six cups of Nestle Lactogen starting newborn formula powdered milk were mixed with 400 mL of sterile distilled water to make a milk solution, and 200 ml of the milk solution was added as an organic source to keep the sludge bacteria growing quickly (Dyosile et al., 2021).

The two anaerobic reactors used were also coupled MBRs with SND capabilities as the final PSW treatment stage. The operation set-up parameters for both reactors are shown in **Table 3-2**, indicating operational temperature, flow rate (0.4 L/h), and calculated HRT (5.54 – 5.90 h) based on the product recovered. Furthermore, both the EGSB and the SGBR were maintained and operated at a temperature of 37.9 – 39.7 °C, with a heating jacket connected to a 37 °C water tank heater controlling the temperature. Heat leakage to the environment was controlled by further sealing the reactors with insulation.

Table 3-2: Operational conditions of the current study for both the EGSB and SGBR.

		Temp (˚C)	Flow rate (L/h)	HRT (h)
EGSB	Feed	39.7	0.4	5.71
	Product	39.7	0.4	5.54
SGBR	Feed	37.9	0.4	5.59
	Product	37.9	0.4	5.90

Samples were collected at different stages of the PSW treatment, recorded, and analysed by CCT scientific service using APHA standard methods as enlisted in the Examination of Water and Wastewater (Association et al., 1912) accreditation document, and computed using QI Macros 2021 which is now available in Microsoft Excel 2016. From the results, removal efficiency (%) of pollutants was calculated using Equation (3) which explains how the removal efficiency was determined.

$$\boldsymbol{The\ removal\ efficiency}\ (\%) = \frac{\boldsymbol{Influent - Effluent}}{\boldsymbol{Influent}}\boldsymbol{x100} \qquad \textbf{Equation 3}$$

Initially, capability analyses of individual stages were done, and subsequently, the multi-stage and multi-response were applied to comparatively assess the lab-scale process designed with previous studies.

3..4 Results

3..4.1 Stage1: Eco-Flush^{TM} facilitated PSW pre-treatment process

Before analyzing the capability of the process in stage one, the average percentage removal efficiency of pollutants in the pre-treatment (alkalinity, COD, FOG, SS, TDS) was evaluated, as can be seen in **Table 3-3**. The average percentage removal efficiency (%) was quantitatively compared with other using pre-treatment systems, i.e. whereby dissolved air flotation (DAF) and Physico-chemical based pre-treatment methods were used. The results of the pre-treatment in the current study agree well with existing studies on the ability to remove alkalinity (31.4%), COD (42%), FOG (7.6%), SS (11.5%, and TDS (56.6%). This is exactly what one would expect from the first stage of a multistage analysis, especially since the current study's findings are lower than in previous studies, but there could be a number of reasons for this, including the fact that the current results were from the first stage of a multistage, whereas previous literature results were from a single-stage design.

Table 3-3: The average percentage removal efficiency (%) in comparison to other pre-treatment studies.

The technology used in different studies	**Removal efficiency (%)**				
	Alkalinity	**COD**	**FOG**	**SS**	**TDS**
DAF in De Nardi et al. (2008)	43	49	-	43	-
DAF in Yoo and Hsieh (2010)	-	80	-	60	100
Physico-chemical based in Hilares et al. (2021)	-	93	92	90	90
Current study	**31.4**	**42**	**7.6**	**11.5**	**56.6**

3..4.2 Stage 2: Anaerobic digestion

3..4.2.1 EGSB

In stage IIa, the final output quality characteristics were influenced by the performance of stage I. **Table 3-4** illustrates the average percentage removal efficiency results using an EGSB in comparison to other studies using similar technology. Subsequently, the results of the performance of an EGSB reinforced the general belief that stage I is highly influential to the performance of secondary processes, anaerobic digestion. The removal efficiency for the EGSB were 4.7% alkalinity, 38% COD, 48.5% FOG, 56.6% SS, and 14.1% TDS.

Table 3-4: The average percentage removal efficiency in different EGSBs and the current study.

	Removal efficiency (%)				
EGSB in different Studies	**Alkalinity**	**COD**	**FOG**	**SS**	**TDS**
Ng and Chin (1988)	5.18	89	-	88	-
Williams (2017)	-	93	92	98	-
Rinquest et al. (2019)	8.4	95.2	93.7	88	6.7
Current study	**4.7**	**38**	**48.5**	**56.6**	**14.1**

3..4.2.2 SGBR

Similar to stage IIa, the quality characteristics of stage IIb were also influenced by the performance of stage I. **Table 3-5** illustrates the average percentage removal performance with findings for stage IIb being 6.1% alkalinity, 35% COD, 28.1% FOG, 53% SS, and 11.7% TDS.

Table 3-5: The average percentage removal efficiency of SGBR in different studies**.**

	Removal efficiency (%)				
SGBR in different studies	**Alkalinity**	**COD**	**FOG**	**SS**	**TDS**
Rajab et al. (2017)	-	97	90	96	-
Rinquest et al. (2019)	86	92.9	-	96.2	-
Njoya et al. (2019)	-	97.32	96.53	97.05	-
Current study	**6.1**	**35**	**28.1**	**53**	**11.7**

3..4.3 Stage 3: Post-treatment.

3..4.3.1 MBR $_{\text{EGSB}}$ (with SND capability)

Table 3-6 represents the typical percentage reduction performance with findings for stage IIIa reporting the removal efficiency of 88% for alkalinity, 58% for COD, 97% for FOG, 84% for SS, and 38% for TSD. As observed with the EGSB, a substantial increase in FOG reduction compared to previous studies, including TDS (57%) and alkalinity (88%) was observed. Although alkalinity removal is not usually a priority in wastewater treatment, it is in this case because if too much alkalinity is removed during the pre-treatments stage, there will be insufficient alkalinity for the biological treatment stages to follow.

Table 3-6: The average percentage removal efficiency with MBR$_{\text{EGSB}}$.

MBR coupled with EGSB in different studies	**Removal efficiency (%)**				
	Alkalinity	**COD**	**FOG**	**SS**	**TDS**
Moore (2015)	-	97	-	99.9	-
Rinquest et al. (2019)	13.8	91	-	97	57
Current study	**88**	**58**	**97**	**84**	**38**

3..4.3.2 MBR $_{\text{SGBR}}$ (with SND capability)

Table 3-7shows the average removal percentage for stage IIIb, which was 85% alkalinity, 87% COD, 38% FOG, 87% SS, and 65% TDS. According to Basitere et al. (2017), the alkalinity removal efficiency was 98.7%, COD removal was 92.4 percent, and SS removal was 99.8%. thus, in contrast to prior research by Basitere et al. (2017) current study has shown an advanced input in removing FOG and TDS.

Table 3-7: The average percentage removal efficiency of MBR$_{\text{SGBR}}$ -SND studies.

MBR coupled with SGBR in different studies	**Removal efficiency (%)**				
	Alkalinity	**COD**	**FOG**	**SS**	**TDS**
Basitere et al. (2017b)	98.7	92.4	-	99.8	-
Current study	**85**	**87**	**38**	**87**	**65**

To assess the performance of the designed lab-scale plant for PSW treatment, the evaluation included a comparison between results of removal efficiency in a variety of designs for SGBR and EGSB combined with pre-and post-treatment technologies from previous studies. The main deductions of different unit performances were drawn together, outlining the results of the overall designed lab-scale plant, with both removal efficiency and CPIs. Based on the results of the removal efficiency of the designed lab-scale plant for PSW treatment (see **Table 3-8**), it was found that such a design, can achieve removal efficiency of 78% (alkalinity), 68% (COD), 92 % (FOG), 80% (SS), and 23% (TDS) when using the EGSB, while for the SGBR only 75%, 88%, 4%, 83%, and 54%, for alkalinity, COD, FOG, SS, and TDS, respectively, could be achieved. In general, this is an interesting finding of the performance for both systems, and it could be hypothesized that although some differences occurred in the two reactors, they both demonstrate the adequacy of treating PSW to some extent.

Table 3-8: Removal efficiency of designed lab-scale plant for PSW treatment.

	Removal efficiency (%)				
Reactors	**Alkalinity**	**COD**	**Fats**	**SS**	**TDS**
EGSB	78	68	92	80	23
SGBR	75	88	4	83	54

Wooluru et al. (2014) explained that process capability indices (PCIs) are a powerful tool for studying process capabilities to meet performance specifications which in this study were alkalinity, COD, FOG, SS, and TDS removal efficiency. Furthermore, CPIS can be more useful for identifying and characterizing a process and its deficiencies. **Figures 3-6, a b, c, d,** and **e** illustrate PCIs analyses for a designed process, for all process units (individually) such that 0.5 degrees of significance are achieved. The sample sizes for all stages were found to be 5, while the mean was respectively 29.82, 32. 38, 26.78, 73.00, and 72.40. Overall, in all stages, P_p and P_{pk} were equivalent and close to unity, i.e. 1, with C_p being equivalent to C_{pk}, with its determined values being 0.99 (Stage I), 1.06 (Stage IIa), 0.83 (Stage IIb), 0.86 (Stage IIIa), and 0.79 (Stage IIIb). Hence one of the key findings from these CPIs' analyses was that in stage IIa, the process has the potential to be capable as CPIs were greater than unity. However, CPIs in other stages were notably less than unity, which indicated that further improvement is required.

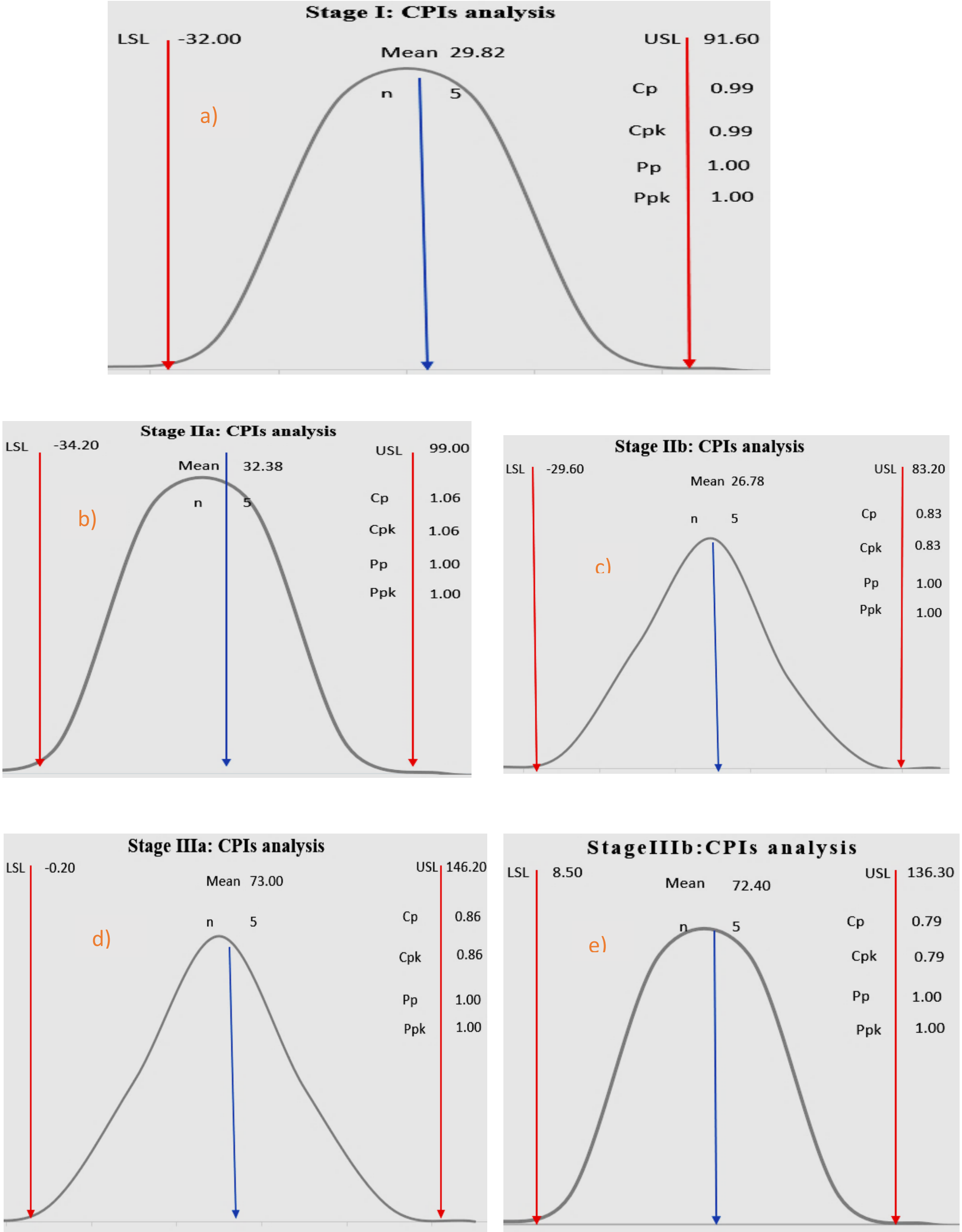


Figure 3-6 : Charts of CPIs analyses under different stages a, b, c, d, and f of the designed process.

As illustrated in **Figure 3-7 a, b** the capability and performance indices of using EGSB and SGBR in comparison with those from previous studies, indicated a reduced performance. In this study, the EGSB and SGBR illustrated similar performance P_p and P_{pk} indices equivalent to unity, although there seemed to be no significant similarity in capability indices C_p, and C_{pk} for both reactors. It was observed in **Figure 3-7 a** that a C_p of 1.06 for the EGSB used in this study was lower than that of 1.2 observed for Rinquest. et al. (2019), 1.18 for Williams (2017), and higher than that 0.62 observed for Ng and Chin (1988). Additionally, **Figure 3-7 b** shows that a C^p of 0.83 for SGBR used in this study was lower than that of 1.12 achieved by Njoya et al. (2019), and 1.13 reported by Rajab et al. (2017). A C_p of 0.78 was reported by Rinquest et al. (2019), which was minutely lower than the one observed for the SGBR used in this study.

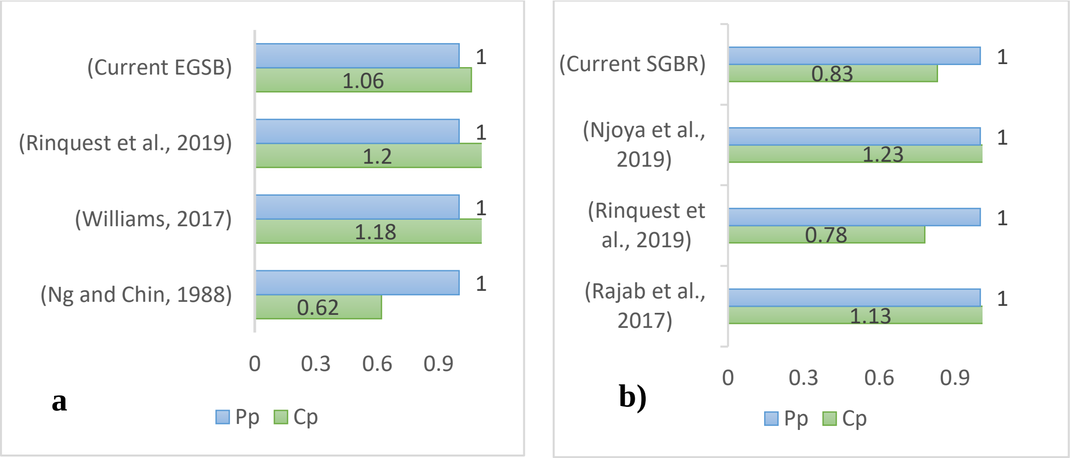


Figure 3-7a, and b: CPIs of both EGSB and SGBR compared to other studies.

To overcome the potential effects of chosen methods for measuring the performance of a designed lab-scale plant for PSW treatment, the quantification of the overall process capability using the multi-stage lab-scale plant, which consisted of a bio-physical pre-treatment and MBR stages, was examined, i.e. evaluating the CPIs for the overall processes. As shown in **Figure 3-8**, C_p and Pp were determined to be 1.17 and 1.00 for the EGSB system, with 1.06 and 1.00 being for the EGSB stage only, while 0.75 and 1.00 were determined for the SGBR system, with 0.83 and 1.00 being for SGBR stage only.

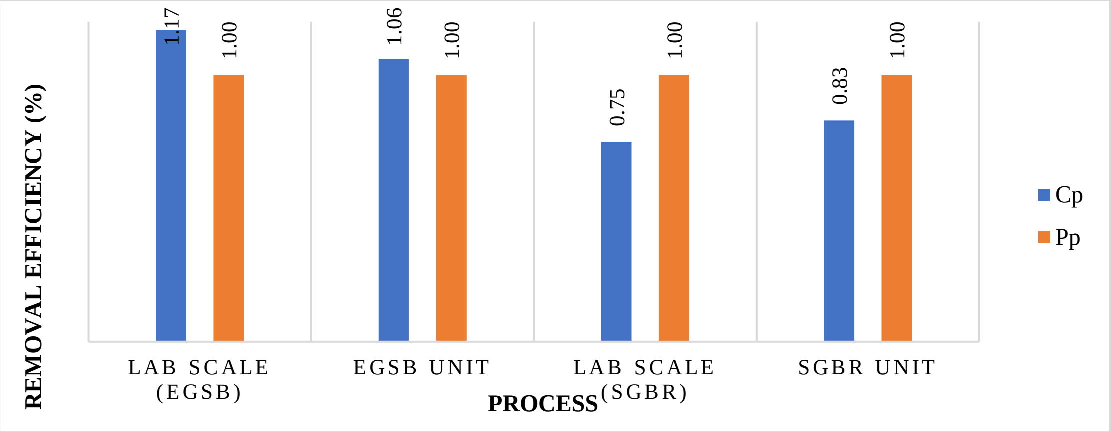


Figure 3-8: Capability indices for the whole process on either unit or lab scale for both EGSB and SGBR.

3..5 Discussion

Understanding the contribution of Eco-flush^{TM} to improved water quality parameters, it was used in a pre-treatment unit for FOG hydrolysis and odour reduction. Its contribution was associated with the reduction of flies, and mosquitos. Its ability to break down one of the listed organic contaminants, i.e. FOG while releasing some solids into the PSW, culminated in better solids removal at the initial stage. Thus, the use of Eco-flush^{TM} improved water quality parameters for the current study which are comparable with others reported in Table 3a. and with an existing study on biological Pre-treatment coupled with the down-flow expanded granular bed reactor (DEGBR) for treatment of PSW, results agree well with different studies of the same scale-plant design. This argument of the potential of the process is consistent with the list of findings of the overall removal efficiency performance of pre-treatment coupled with DEGBR in terms FOG, COD, and TSS, was 97 ± 0.8%, 92 ± 6.3%, and 97 ± 1.2% respectively (Dlamini et al., 2021), again the potential of process observation agrees with the system (pre-treatment–EGSB–MBR) exceeded 97% for TSS and COD removal and 97.5% for FOG removal, which was similar to that investigated in the study of Meyo et al. (2021). Furthermore, Phumeza et al., (2021) assessed the performance of an integrated multistage lab-scale plant and found 87%, 93%, and 90% for COD, TSS, and FOG, respectively. Even though the current pre-treatment design's removal effectiveness was reported as being lower than that of previous examples, i.e. DAF/Physico-chemical pre-treatment experiments (see Table 3a), previous studies have utilized varied operation conditions for optimum operation, such a variation would be unknown until optimization studies are conducted. By comparing the findings in Table 3a and Table 4, the present pre-treatment strategy has made a significant contribution to the overall performance of lab-scale removal efficiency for both systems evaluated.

In the course of comparative analysis in this work, considering both removal efficiency and CPIs as performance indicators, it was observed that removal of Alkalinity was increased for both the PT-EGSB and PT-SGBR trains, albeit with only the PT-EGSB train removing significant FOG than the SGBR, further suggesting that more than 99 % of the output from stage I of the process can meet the requirements under optimum conditions. Besides the differentiated PSW feeding design of the EGSB (bottom PSW feeding) and SGBR (top PSW feeding), the performance of the EGSB seemed to be a better technology in terms of FOG removal in comparison to the SGBR, meaning a bottom PSW feeding approach is the best strategy for designs focusing on PSW treatment. This suggests an even distribution of the PSW in the EGSB than in the SGBR which is prone to wastewater channelling caused by dead zones. This assertion agreed well with the existing study of Basitere et al. (2020) whereby a review of up-flow vs downflow anaerobic digester reactor configurations for treatment of fats-oil-grease laden suggested that a redesign is required perhaps to have both the attributes of the EGSB and SGBR. Furthermore, in a bottom PSW feeding system, bed expansion provides nutrients throughout the bed designed by granules. This was also evident in terms of COD/SS/TDS removal efficiency (see Table 3b). The concept of a down-flow expanded bed granular bed reactor was evaluated, and the interest in alkalinity and some FOG removal findings is consistent with previous studies on the importance of biological processes such as nitrification and anaerobic digestion performance, which could be related to previous findings (Njoya, 2019). Alkalinity is an important factor that influences whether treated water can be disposed of safely into the environment, with FOG being of primary interest for PSW treatment. Such high-strength wastewater requires an anaerobic treatment system with higher efficacy to ensure excellent treatment performance. This is suggested by the Alkalinity removal efficacy at 75 -78 % for lab-scale systems used, and FOG at 92 % on the EGSB train (see Table4).

For treated water polishing, it was unsurprising to find that there is a considerably better performance for the MBRs used as they use membranes for solid-liquid separation gave the combined benefits of biological waste degradation and physical membrane filtration when compared to the pre-treatment unit whereby only a hydrolysis agent was added. However, both are physical processes, normally a pre-treatment to a bioreactor system can be amended to use air bubbles to remove solids after flocculation and floc removal. Depending on the intended use of the final treated water, i.e. the pre-treated PSW, it will be beneficial to combine both biological waste degradation and membrane filtration. Overall, the performance of MBRs depends on one of its preceding stages. MBRs removed more alkalinity and some residual nutrients. Several studies used for comparative analysis focusing on PSW treatment solely used the EGSB and SGBR and even when pre-treatment units were used, they were operationally different. Hence, this study set-out to preliminary assess and monitor the quality performance of a designed process, i.e.Bio-physical pre-treatment)- EGSB or SGBR-(MBR), to ascertain whether such a combination of systems can be used at a PSW plant. Therefore, as a prospective study, various factors need to be further assessed for optimum performance, even when some performance indicators indicated individual and whole system capability.

3..6 Conclusion and recommendations

The study aimed to monitor the quality performance of a designed process [(Bio-physical pre-treatment) - (EGSB & SGBR) - (MBR)] at a PSW plant, and the main conclusions of this work are drawn together and presented in this section, as there has been an increased recognition that more attention needs to be paid to EGSB and SGBR coupled with either pre-or post-treatment for PSW performance. Then, in the current study, the performance and capability of a design of both reactors (EGSB and SGBR) coupled to pre-and post-treatment was a research topic that got a lot of attention. As a result, our selection of CPIs for alkalinity removal, COD, FOG, SS, and TDS process analysis appears to be adequate. In general, the average of in and effluents samples acquired in each step of this investigation were within the limit set by the City of Cape Town by-laws and SANS 241: 2011 in this section (see Table 1). We found that, except for stage IIa, all other stages had Cp and Cpk lower than 1, there was an indication of high-quality results, with more than 75 % of the output from all stages of the process fulfilling the criteria. Future research seeking to use this methodology should attempt to understand why Cp and Cpk were less than 1, and it is suggested that experimental data be used to either determine the effectiveness of (PT-SGBR/EGSB-MBR) coupled with Ultraviolet Light (UV) or to determine the effectiveness of these processes by considering more parameters and over a longer period.

Author Contributions: N.N. collected the data, analyzed and interpreted the data, and drafted the manuscript. M.B., D.M, and S.K.O.N. conceptualized the study, revised the manuscript, and analyzed the data. All authors have read and agreed to the published version of the manuscript.

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Appendix A:

Capability of Anaerobic Bioreactors for a Poultry Slaughterhouse Wastewater Treatment

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***Abstract*—**Poultry slaughterhouses use as a high quantity of clean water as generate a high volume of wastewater, and anaerobic digestion process known to be an effective way to treat such wastewater at low operation cost. The prominent anaerobic digesters, namely Static Granular Bed Reactor (SGBR) and down flow Expanded Granular Sludge Bed reactor (EGSB) have been appreciated to treat the poultry slaughterhouse wastewater. Previous studies have assessed the performance capacity of both SGBR and EGSB based on their criteria for chemical Oxygen Demand (COD) removal efficiency. By contrast, the quality of these reactors depends on multiple characteristics COD removal (%),Fat, Oil and Grease(FOG) removal (%), Biological Oxygen Demand (BOD) removal (%), Hence a case study approach was used to test their effluent potential, by hypothesis testing multivariate capabilities for both EGSB and SGBR at PSW pilot plant. The visual basic program of excel as statistical software

.

***Index Terms*—**Expanded Granular Sludge Bed, Multivariate process capability indices, Poultry slaughterhouse wastewater, Static granular bed reactor.

I. INTRODUCTION AND BACKGROUND

Poultry slaughterhouse is associated with water consumption and a high amount of wastewater generated. The major environmental problem associated with slaughterhouse wastewater is a large amount of organic matter [1] Although a number of cross-sectional studies suggest that better effluent quality of wastewater treatment works is an option to the water resources, due to the growth in environmental limitations that has to be effectively monitored [2]. There is evidence that increasing the need for more efficient water treatment and management, plays a crucial role in attending to the freshwater resource’s challenges in both urban and industrial area [3] Debate continues about the best strategies for such management.

The biological anaerobic treatment process is one of the industrial wastewater treatments that is substantiated by biodegradability, treatability. Nowadays, there increase in anaerobic bioreactor use for wastewater treatment plants due to their performance, efficiency, and cost-effectiveness. EGSB and SGBR being ones of low-cost biological treatment processes. This study aimed to analyze the capability of both EGSB and SGBR for removing COD, BOD, and FOG from a pilot PSW plant. A case-study approach was chosen to allow a deeper insight into EGSB and SGBR organics (COD, BOD, and FOG) removal performance using data of record in the previous work of Basitere, Williams [4].

II. PROCESS CAPABILITY EVALUATION

Generally, the purpose of monitoring the process is to assist the plant performance to satisfy its operating objectives. Although, the operation of the plant depends on size, and correlation of process variables. It is then important to point key variables that can have significant consequences for plant safety, the environment, product quality, and plant profitability. Hence methodology involved steps as shown in Fig.1.

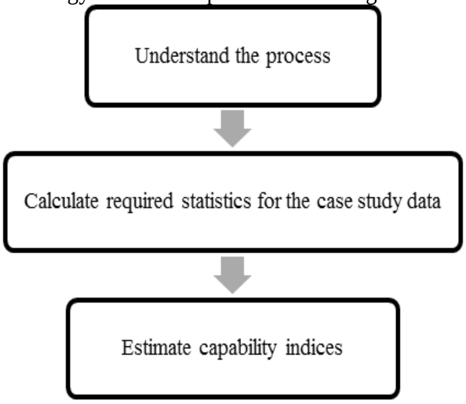

Fig. 1. Capability analysis procedure

A. *Case Study and Data*

The case study related to measuring the capability and performance of effluents of EGSB and SGBR reactors to remove organics (COD, BOD, and FOG). Generally, data must be collected in such a way they are appropriate, differ from their costs, time and other resources at the disposal of the research [5]. Hence primary and secondary data from at PSW pilot plant-like COD removal (%), FOG (%), BOD (%) recorded in the previous work of Basitere, Williams [4] shown in Table I; Sample of an experimental data of organics removal through SGBR presented in Table II, and Table III exemplifies Organics removal standards. They were used to examine the

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TABLE I: SAMPLE OF AN EXPERIMENTAL DATA OF ORGANIC MATTER REMOVAL BY EGSB

Day	COD removal (%)	BOD removal (%)	FOG removal (%)
7	73,02	84,71	87,14
14	97,03	98,59	95,54
21	97,54	98,91	94,68
28	93,16	94,67	92,34
35	94,36	98,29	91,16
42	97,10	99,23	93,77
49	97,44	98,76	94,83
56	95,33	92,80	85,46
63	97,34	98,82	96,28
70	94,95	98,48	98,07
77	96,39	98,83	96,64
84	97,96	97,84	96,99
91	99,61	99,88	99,42
98	99,06	99,51	98,17
105	97,22	98,29	84,57

TABLE II: SAMPLE OF AN EXPERIMENTAL DATA OF ORGANIC MATTER REMOVAL BY SGBR

Days	TCOD removal (%)	BOD removal (%)	FOG removal (%)
28	74,1	93	45,3
29	78,0	94	82,8
27	78,6	91	91,8
28	85,5	96	93,6
26	85,4	93	89,7

TABLE III: ORGANIC MATTER REMOVAL STANDARDS

Parameter	S. D (σ)	Min	Max	Median
TCOD removal (%)	3,63	49,39	98,05	95,68
BOD average (%)	4,54	84,71	99,23	98,59
FOG removal (%)	3,58	85,46	96,28	93,77

A. EGSB, SGBR, and Organics (COD, BOD, and FOG) Removal Process Overview

Normally process outputs (Ys) are subjected to the inputs (Xs), and to monitor the process, requires linking outputs to the needs (quality) and expectations of the customer. Quality practitioners associate the Voice of the Process (VOP) with the Process Output Variables (POV). By considering VOP, as an operation of all the inputs. Fig. 2 illustrates the organics removal process through either EGSB or SGBR. COD is used to test the concentration of organic matter, while BOD helps to test the organic matter in wastewater. FOG components in wastewater, have low solubility that lower biodegradability by microorganisms.

Poultry slaughterhouse wastewater has led to a concern of high organics, hence confronted by the quality standard to fit recycling and reuse. SGBR and EGSB being some of the technology extensively used to treat PSW, and by contrast, these reactors need adequate monitoring in the organics removal process. As the aim was to Test and analyze capability performance for organics (COD, BOD, and FOG) removal through EGSB and SGBR, The capability analysis procedures based on multivariate characteristics of a sample of experimental data in Table I and II from at PSW pilot plant, was evaluated.

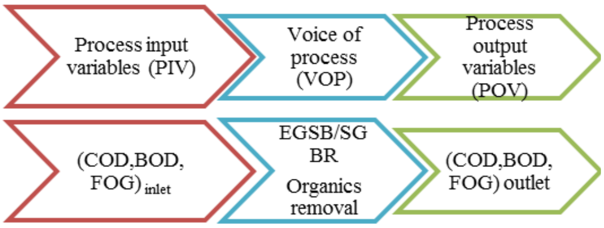

Fig. 2. Process overview.

B. Final Stage Organics (COD, BOD, and FOG) Removal Process Capability Analysis in EGSB and SGBR

According to Scagliarini [6] multivariate capability index MCpm is given by the volume of engineering tolerance region divided by the one of modified process region, as shown in Eq. (1).

$$MC_{pm} = \frac{C_p}{D} \qquad (1)$$

Where *Cp* stands for the process variability comparative to the modified tolerance region, and *D* stands for the process deviation from the target. For estimating the MCpm index, there is a need for a random sample n, the number of characteristics v (dimension), α value to define the size of the tolerance region (usually α =0.0027). The sample data in Tables I, II, and III were processed respectively to assess the capability of EGSB and SGBR for organics removal processes of a pilot PSW plant.

C. Assumptions

i. The organics removal processes through EGSB and SGBR are stable and approximately normally distributed.

ii. The organics removal processes through EGSB and SGBR do not depend on temperature, HRT, and OLR.

D. Hypothesis Testing for Organics (COD, BOD, and FOG) Removal Process Capability

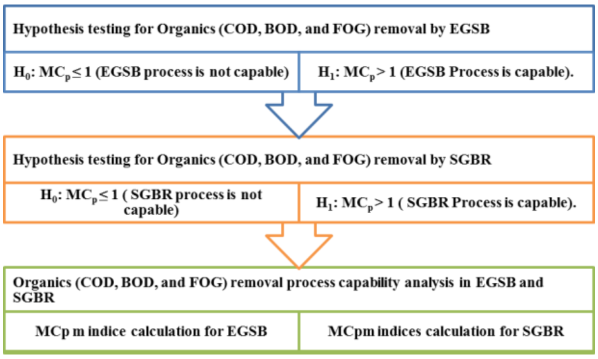

Fig.3: Hypothesis testing for Organics (COD, BOD, and FOG) removal process capability.

Following the steps shown in Fig. 3, it was determined whether or not Organics (COD, BOD, and FOG) removal processes were capable.it was done based on data from Table I and II from at PSW pilot plant, and using an excel

Following the steps shown in Fig. 3, it was determined whether or not Organics (COD, BOD, and FOG) removal processes were capable.it was done based on data from Table I and II from at PSW pilot plant, and using an excel spreadsheet with instructions provided by Scagliarini [6], MCpm indices were estimated.

I. Results and Discussion

MCpm indices (MCpm, MCP, and D) were calculated via excel software, and outputs are shown in Table IV. Where index (MCpm) was found to be 0.06, which means the multivariable of COD, BOD, and FOG removal process capability analysis in EGSB has been found to have a bigger variation than allowed by the specification limits. Secondly, MCP (the modified tolerance region) was found to be 0.11 and the volume of the scaled 99.73 percent process region (D) was 1.79 which means that the closeness of process means to the target was 1/(1, 79).

Based on the value of MCP of 0.11 that was smaller than one, COD, BOD, and FOG removal process capability analysis in EGSB revealed that the EGSB process was incapable at 0.0027 level of significance.

MCpm indices (MCpm, MCP, and D) were calculated via excel software, and outputs are shown in Table V, and index (MCpm) was found to be 0.04, which means the multivariable of COD, BOD, and FOG removal process capability analysis in SGBR has found not to conform with presumed by the specification limits. Secondly, MCp (the modified tolerance region) was found to be 0.22 given the scaled volume of 99.73 percent process region. D was 4.95 which means that the closeness of process means to the target was 1/ (4, 95).

Based on the value of MCp of 0.22 that was smaller than 1, Organics (COD, BOD, and FOG) removal process capability analysis in SGBR revealed that the SGBR process was incapable at 0.0027 level of significance.

TABLE IV: EGSB Capability Indices Results

MCpm index	value
MC_{pm}	0,06
MC_{p}	0,11
D	1,79

TABLE V: SGBR Capability Indices Results

MCpm index	value
MC_{pm}	0,04
MC_{p}	0,22
D	4,95

II. Conclusion

This study set out to assess whether organics (COD, BOD, and FOG) removal by both EGSB and SGBR processes were capable at 0.0027 level of significance. This research found both processes incapable; hence a design of EGSB or SGBR coupled with both pre and post-treatment should be an option. Also, this study can be extended to develop nutrients and solids removal processes for EGSB and SGBR.

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Appendix B: Extended abstract of 12th Eastern European Young Water Professionals Conference. 31 March -2 April 2021, Riga, Latvia

Capability Analysis of a Multi-Stage Process Design in Poultry Slaughterhouse Wastewater Treatment Systems

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INTRODUCTION

Wastewater treatment plays a critical role in water resource repossession, although the existing literature focuses on poultry slaughterhouses that generate significant volumes of wastewater (Aziz et al., 2018). The quality of poultry wastewater is measured by organics, nutrients, and solids. In most recent studies, Static Granular Bed Reactor (SGBR) and Expanded granular sludge bed found to be one of the most widely used reactors and have been extensively used for treating different types of wastewaters including PSW. Prior research has analyzed EGSB and SGBR independently, and there is still a need for treated PSW, to meet the requirements. The current study aimed to develop and evaluated the applicability of the capability of a case study on the multi-variate stages (PT-SGBR/EGSB-MBR) of PSW treatment processes. It was then predicted that the same approach will be applied to the targeted process illustrated in Figure1, using the secondary experimental data and QI macros software designed in excels.

MATERIALS AND METHODS

The literature discusses on use of Process capability indices (Cpk and Cp) in the different industries (Aslam et al., 2019) and describes the multi-stage processes(Sarkar, 2019). Hence these methods were preferred to measure the performance of the designed plant.

Pilot plant design

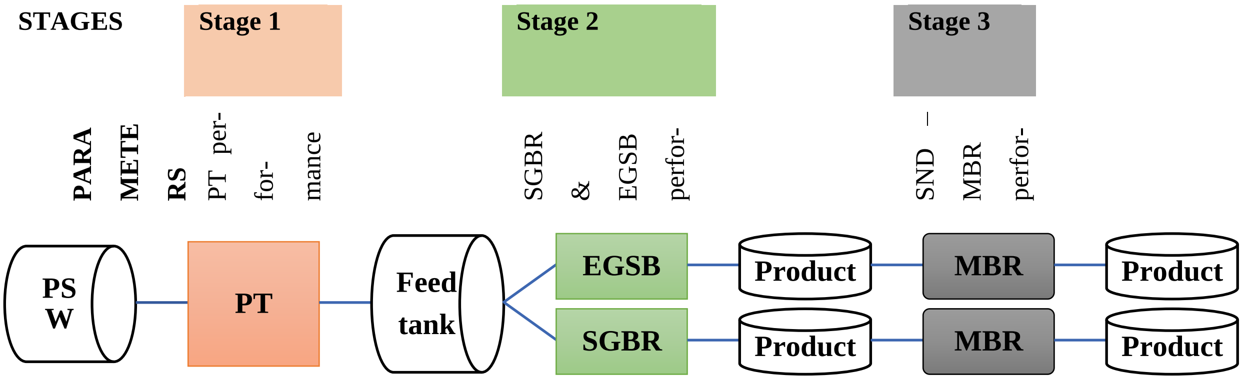

Figure 1. Illustrated targeted design of multi-variate and stage process for a pilot PSW treatment plant.

Data collection and analysis

In the designed process illustrated in Figure 1, the quality of poultry wastewater parameters like Alkalinity, COD, Fats, Suspended Solids (SS), Total Dissolved Solids (TDS) were measured. These parameters were randomly extracted and recorded in a designed excel spreadsheet, and then analyzed. Figure 2 sketches the working out of Cp and Cpk, for the overall process. Furthermore, it was assumed that the data were normally distributed.

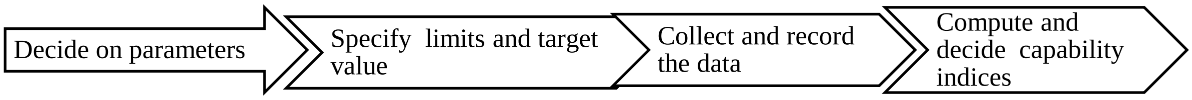

Figure2. Flamework Compute Cp and Cpk indices in a designed excel spreadsheet.

RESULTS AND DISCUSSION

Table 4 illustrates sample sizes (n=15), respective means (35.745; 37.548), and SD (34.106; 33.367) the potential and capability of the overall process were significant, where through SGBR, the Cpk (1.40) and Cp (1.40) is greater than 1.3. Similarly, Cpk (1.54) and Cp (1.54) in EGSB are also tabled.

Table 4. Process capability indices estimation**.**

	Process through EGSB	**Process through SGBR**
n	15	15
Mean	35.745	37.548
SD	34.106	33.367
Cpk	1.54	1.40
Cp	1.54	1.40

CONCLUSION

The capability of a Multi-stage process design in poultry slaughterhouse wastewater treatment systems was intended, the capability was analyzed for both performance and potential into the removal of Alkalinity, COD, Fats, SS, TDS from the multistage process (PT-SGBR/EGSB-MBR). The finding on the overall performance indicated its capability to meet the requirements. Further research to determine the effectiveness of (PT-SGBR/EGSB-MBR) coupled with and UF, and more parameters is then recommended.

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