2021-01

Performance investigation of the slaughterhouse wastewater treatment facility: a case of Mwanza city slaughterhouse, Tanzania

Michael, Semba

NM-AIST

https://doi.org/10.58694/20.500.12479/1283

PERFORMANC EINVESTIGATION OF THE SLAUGHTERHOUSE WASTEWATER TREATMENT FACILITY: A CASE OF MWANZA CITY SLAUGHTERHOUSE, TANZANIA

Semba Yunus Michael

A Dissertation Submitted in Partial Fulfillment of the Requirements for the Degree of Master's in Hydrology and Water Resources Engineering of the Nelson Mandela African Institution of Science and Technology

Arusha, Tanzania

January, 2021

ABSTRACT

The present study engaged onsite operations and laboratory analysis for Mwanza City Slaughterhouse (MCS) wastewater to improve the efficiency of wastewater treatment of a newly installed facility. The MCS wastewater treatment facility integrated with various units-biodigester (Batch Stirred Tank Bio-reactor), aeration unit, retention, clarifier, and a constructed wetland. During the initial runs, the MCS facility removed 87.5%, 92.2%, 43%, and 65.4% of effluent biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), ammonium, and nitrate, respectively. Also, the parameters including pH, temperature, dissolved oxygen (DO) were used to control the system operations. After conducting effective plant operations for five months, the removal efficiencies of BOD_5, COD, ammonium, and nitrate improved to 97.4%, 98.3%, 97.4%, and 97.6%. In the present study, the unit-by-unit performance values achieved as a result of alterations of the facility's running conditions presented. The MCS wastewater treatment facility found to be energy-positive, as it produced an average of 158.2 m^3 biogas per day. This amount of biogas, if converted to electricity, would be sufficient to run the facility operations. Generally, the MCS wastewater treatment facility attained the best performance as per design, achieving the effluent levels recommended by the Tanzania Standards (TZS). Also, the MCS treatment facility takes care of the environment and human health because of effluents released to the surrounding area are now within recommended standards.

DECLARATION

I, Semba Yunus Michael, do declare to the Senate of Nelson Mandela African Institution of Science and Technology that this dissertation is my own original work done within the period of registration under the guidance of supervisors and that it has neither been submitted nor is being concurrently submitted for degree award in any other institution.

Semba Yunus Michael

Name and Signature of Candidate

11 March, 2021

Date

The above declaration is confirmed by:

Prof. Karoli N. Njau

Name and Signature of Supervisor (1)

16/03/2021

Date

Dr. Mwemezi J. Rwiza

Name and Signature of Supervisor (2)

11/March/2021

Date

CERTIFICATION

The undersigned certify that they have read and therefore, recommend for acceptance by the Nelson Mandela African Institution of Science and Technology the dissertation entitled "Performance Investigation of the Slaughterhouse Wastewater Treatment Facility: A Case of Mwanza City Slaughterhouse, Tanzania" in fulfillment of the requirements for the degree of Master's in Hydrology and Water Resources Engineering of the Nelson Mandela African Institution of Science and Technology.

Prof. Karoli N. Njau   Date: 16/03/2021

Dr. Mwemezi J. Rwiza   Date: 11/March/2021

ACKNOWLEDGEMENTS

I want to thank the Almighty God for His help toward completing this task, without whom this task would not have been feasible. I would also like to thank my supervisors Professor Karoli N. Njau and Dr. Mwemezi J. Rwiza, who tirelessly assisted and advised me until the completion of this research. I have learned various things from them as leaders, persons and supervisors who have changed my reasoning as a person and a researcher. May God bless you both. Likewise, I would like to thank WISE-Futures African Center of Excellence (ACE) for funding my research to its end. Finally, I would like to recognize my colleagues at the Nelson Mandela African Institution of Science and Technology who assisted me in many different ways to make this task possible; Dr. Thomas Kivevele, Joseph Maximillian, Chrisogoni Paschal, Paul Mtae, Patrick Kimbuya, Teresia Kimario, Saidi Galambo, Justine Lwekoramu, and Paulo Sanka. Thanks a lot.

DEDICATION

This work is dedicated to my family for their constant support.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS AND SYMBOLS

APHA	American Public Health Association
BOD	Biological Oxygen Demand
CFU	Colony Forming Units
$CaCO_3$	Calcium Carbonate
COD	Chemical Oxygen Demand
EC	Electrical conductivity
kWh	Kilowatt-hour
MCS	Mwanza City Slaughterhouse
MCC	Mwanza city council
NM-AIST	Nelson Mandela African Institution of Science and Technology
NTU	Nephelometric Turbidity Unit
ppm	Parts per million
Pt-Co	Platinum-Cobalt
rpm	Revolution per minute
SWW	Slaughterhouse Wastewater
VFAs	Volatile Fatty Acids
TDS	Total dissolved solids
TSS	Total Suspended Solids

CHAPTER ONE

INTRODUCTION

1.1 Background of the Problem

The meat industry generates enormous volumes of wastewaters that come from cleaning slaughterhouse facilities, meat processing and cleaning animal carcasses (Bustillo-Lecompte & Mehrvar, 2015). The volume of these wastewaters being released into the receiving environment has also increased over the years due to increased meat production to meet the protein requirements of growing human populations (Emmanuel *et al.,* 2016). Slaughterhouse wastewater contains biodegradable suspensions, colloidal particles, organic matter, fats and cellulose, which usually contribute to elevated chemical oxygen demand (COD) and biological oxygen demand (BOD) (Shujun *et al.,* 2015). These materials can eventually reduce the amount of dissolved oxygen (DO) in the receiving aquatic environments (Sunder & Satyanarayan, 2013). Thus, slaughterhouse wastewater requires considerable treatment to eliminate environmental contaminants before being discharged into the receiving aquatic environments (Irshad *et al.*, 2015).

The present study dealt with wastewater treatment processes at a newly installed Mwanza City Slaughterhouse (MCS) wastewater treatment plant in Tanzania. Before the MCS wastewater treatment facility installed, the influent used to be released untreated to the nearby receiving waters that empty into Lake Victoria. The untreated slaughterhouse wastewater required a substantive treatment to resolve pollution problems related to industrial effluents that feed into Lake Victoria.

The Nelson Mandela African Institution of Science and Technology (NM-AIST) designed and supervised the construction of a slaughterhouse wastewater treatment facility for MCS. The design flow rate of wastewater into the facility was 130 m^3 per day. Other design parameters for influent quality of the MCS wastewater treatment facility, with their values indicated in parentheses, were as follows: pH (7.5), wastewater colour (10750 Pt-Co), TSS (9700 mg/L), BOD_5 (1200 mg/L), COD (4500 mg/L), NH_3-N (65 mg/L), SO_4^{2-} (370 mg/L), and faecal coliform (2 x 10^7 CFU/100 mL). The mean initial two-month performance after the construction of the MCS wastewater treatment facility revealed that effluent contaminant levels were above the TZS regulation (Table 1).

Table 1: Initial performance (two months) levels of the Mwanza City Slaughterhouse wastewater treatment facility compared to the maximum allowed guidelines by the Tanzania Standards (TZS)

Parameter	Influent	Effluent	Allowed TZS limits	Overall efficiency (%)
BOD_5 (mg/L)	1013 ± 128	127 ± 19	30	87.5
COD (mg/L)	4606 ± 582	359 ± 28	60	92.2
TSS (mg/L)	9592 ± 105	134 ± 14	100	98.6
NH_4^+	73.8 ± 2.1	42.1 ± 1.3	10	43
Fecal Coliform (Counts/100 mL)	32000 ± 869	750 ± 32	1000	97.7
NO_3^- (mg/L)	338 ± 18	117 ± 12	50	65.4
NH_3 (mg/L)	582 ± 34	89 ± 8	N.I.*	84.7
Turbidity (NTU)	9859 ± 128	393 ± 39	300	96

*N.I. = Not indicated in the standards

The designed MCS wastewater treatment facility consisted of several units e.g., pretreatment unit (screening, oil, and fat/grease trap and buffer tank), biodigester unit (Batch Stirred Tank Bio-reactor), advanced treatment (aeration tank and clarifier) and a polishing step (constructed wetland). Also, the facility has subcomponents e.g., a biogas holder and a sludge drying bed. This design makes it one of the novel systems that have, so far, not extensively studied. During the study, the MCS wastewater treatment facility was energy-positive because the daily energy consumption ranged between 50 and 65 kWh. In contrast, the daily biogas production ranged from 220 to 250 kWh, if converted into electricity. However, at the time of the study, the biogas produced was not used for power generation because the utilities for power production were yet to be procured and installed. Furthermore, the initial production of biogas from the MCS wastewater treatment facility was below the estimated potential of 200 m^3 per day. Therefore, the present study aimed to investigate the performance of the MCS wastewater treatment facility by taking into account the factors that affect operational efficiencies.

1.2 Statement of the Problem

The MCS discharged untreated wastewater from slaughtering activities to the receiving environment due to the absence of the wastewater treatment facility. The untreated slaughterhouse wastewater was emptied into the Lake Victoria–a point source pollution of the lake. The MCS wastewater treatment facility's baseline study showed that the MCS wastewater has a high load of COD (2348 mg/L) and BOD_5 (1013 mg/L). However, after installation of a new MCS treatment facility, the initial performance was below expectation and the system required to be optimized.

Also, the MCS wastewater treatment system processes needed electrical power mainly for pumping the wastewater to the treatment facility, agitation and security lighting. This power is supplied from the national grid. The power supplied from the national grid is costly for the MCC to afford, resulting in improper operations of the treatment facility due to delays in purchasing power for the facility. Any power supply interruption would cause the facility to stop functioning.

Furthermore, the power supply was anticipated to be solved with enough generation of biogas at the MCS treatment facility. It was observed that, the MCS biodigester (Batch Stirred Tank Bio-reactor) unit produced abiogas of around 95 m^3 per day. This amount of biogas was inadequate compared with the anticipated design potential of 200 m^3 in a day. This situation was probably caused by imperfect processes or operational conditions as well as a loss of active biomass during the system operations. Therefore, there was a need to carry out a study to find out the operating conditions that may improve the facility's functioning.

1.3 Rationale of the Study

Wastewater and, in particular, slaughterhouse wastewater is a burden to environmental and human health. If not properly handled and treated, wastewater may be detrimental to terrestrial as well as aquatic life. When slaughterhouse wastewater reaches the receiving waters such as Lake Victoria untreated, harmful effects are usually inevitable. Animal waste-linked wastewaters are usually rich in nutrients e.g., N and P, and these nutrients have chemical and biological effects on the aquatic environments (Shujun *et al.,* 2015). Also, the MCS wastewater was used to be discharged untreated and channeled into the Lake Victoria-a point source of the lake. Therefore, slaughterhouse wastewater requires considerable treatment to eliminate contaminants before being discharged into receiving water bodies (Irshad *et al.,* 2015).

1.4 Research Objectives

1.4.1 General Objective

The general objective of this research was to investigate the performance of the slaughterhouse wastewater treatment facility.

1.4.2 Specific Objectives

(i) To establish the Mwanza City slaughterhouse wastewater quality and the necessary conditions for biogas production.

(ii) To understand the operational conditions that will lead to the release of effluent at an acceptable quality.

(iii) To establish the necessary conditions that will lead to optimisation of the Mwanza city slaughterhouse treatment facility.

1.5 Research Questions

(i) What are the effluent quality levels and prevailing operational conditions of the Mwanza City slaughterhouse wastewater treatment facility?

(ii) What can be done to improve the overall efficiency of the Mwanza City slaughterhouse wastewater treatment facility?

(iii) What are the optimal operating conditions for effective and sustainable treatment of the slaughterhouse wastewater?

1.6 Significance of the Study

The present study targeted to generate information that would be useful in operation and performance conditions for slaughterhouse wastewater treatment facilities. This information would also provide conditions for improving biogas production as an energy source, which may be useful for electricity and heat generation for the plant use and surrounding communities. The information acquired from this study delivers valuable scientific evidence to guide slaughterhouse wastewater treatment operations at MCS and other similar facilities. Furthermore, the study provides essential recommendations to reduce pollution risks that would, in the future, impact both human and environmental health.

1.7 Delineation of the Study

The present study dealt with wastewater treatment processes at a newly installed Mwanza City Slaughterhouse (MCS) wastewater treatment plant in Tanzania. The Nelson Mandela African Institution of Science and Technology (NM-AIST) designed and supervised the construction of a slaughterhouse wastewater treatment facility for MCS. The design flow rate of wastewater into the facility was 130 m^3 per day. The mean initial two-month performance after the construction of the MCS wastewater treatment facility revealed that effluent contaminant levels were above the TZS regulation. Furthermore, the initial production of biogas from the MCS wastewater treatment facility was below the estimated potential of 200 m^3 per day. Therefore, the present study aimed to investigate the performance of the MCS wastewater treatment facility by taking into account the factors that affect operational efficiencies.

CHAPTER TWO

LITERATURE REVIEW

2.1 Overview of Slaughterhouse

Generally, slaughterhouse facilities generate a high amount of wastewaters ranging between 1.0 and 8.3 m^3 per animal per day thorough cleaning and meat processing activities (Ahmadian *et al.,* 2012). The wastewaters from slaughterhouse facilities contain high concentrations of biodegradable suspensions, colloidal particles, organic matter, fats and cellulose that contributes to elevated chemical oxygen demand (COD) as well as biochemical oxygen demand (BOD_5) (Caixeta *et al.,* 2002). These wastewaters require substantial treatment before being released to the environment. Globally, various treatment methods have been used to treat slaughterhouse wastewaters. These include, but are not limited to, fine screening, sedimentation, trickling filters, coagulation-flocculation and activated sludge processes (Bazrafshan *et al.*, 2012). Regardless of opting for these treatment methods, proper operation management is essential to meet its expected performance (De Nardi *et al.,* 2011).

2.2 Importance of Slaughterhouse Waste Water Treatment

Well-organized disposal of effluent from meat-processing works is essential due to the potential pollution of water sources and the environment. The effluent discharged from slaughterhouses can cause deoxygenation of water sources and groundwater pollution (Amorima *et al.*, 2007). Therefore, the treatment facility is crucial in all slaughterhouses or meat processing industries. The treatment facility can help to discharge the slaughterhouse effluent, which complies with the recommended discharge limits if the operations are well monitored (Aziz *et al.*, 2019). The treatment facility does not safeguard the environment only but also generates valuable products such as energy and organic fertilizer as well as climate change reduction.

2.3 Slaughterhouse Wastewater Composition

The effluents from meat processing are considered harmful due to the Slaughterhouse Wastewater (SWW) complex composition of proteins, fibers, fats, oil and grease, pathogens, pharmaceuticals, and high organic content for veterinary purposes (Bustillo-Lecompte *et al.*, 2015). This complex composition or characteristics of the slaughterhouse wastewater may affect the suitability of land-application for agricultural use (Wu & Mittal, 2012). The slaughterhouses' effluents are characteristically assessed through bulk parameters because of the pollutant loads and broad range of the slaughterhouse wastewaters. In Table 2 (Bustillo-Lecompte *et al.,* 2015), the environmental pollution indicators from the slaughterhouse wastewater are detailed.

Table 2: General characteristics of the slaughterhouse wastewater

Parameter	Range	Mean
TOC (mg/L)	70-1200	546
BOD_5 (mg/L)	150-4635	1209
COD (mg/L)	500-15900	4221
TN (mg/L)	50-841	427
TSS (mg/L)	270-6400	1164
pH	4.90-8.10	6.95
TP (mg/L)	25-200	50
Colour (Pt-Co)	175-400	290
Turbidity (NTU)	200-300	275

2.4 Environmental Pollution Indicators of Slaughterhouse Wastewaters

2.4.1 Biological Oxygen Demand (BOD)

The BOD is the environmental pollution indicator used to determine quickly biodegradable constituents in an effluent. A known volume of the effluent is incubated at 20°C for five days. It is added to a well-known volume of oxygen-saturated water and is used to measure the oxygen eaten by aerobic microbes. The BOD presence in slaughterhouse wastewaters is an indicator of the biological oxidation of organic materials; high concentrations mean high availability of microbial loads (Yaakob *et al.,* 2018). The BOD generated from slaughterhouses, being untreated, becomes a source of potential pollution inline production (Melo *et al.,* 2008). Slaughterhouse wastewater requires intensive treatment for safe discharge (Abdurahman *et al.*, 2015; Latif & Dickert, 2014). Also, a strict regulation to protect the environment and human health should be taken to overcome this condition.

2.4.2 Chemical Oxygen Demand (COD)

A determination of oxygen needed for the oxidation of organic matter using a standard technique in a known volume of effluent. The COD is frequently used as a more accurate and cheaper means of determining the oxygen required for an effluent before treatment. Also, the

COD parameter as another main chemical characteristic of the slaughterhouse wastewater, disclose the organic content levels (Yaakob *et al.*, 2018). The high amount of COD specifies the existence of high chemical reaction among organic materials in the slaughterhouse wastewater.

2.4.3 Nitrogen Compounds

Occurs in three forms in slaughterhouse wastewater included ammonia (NH_4^+, NH_3-N), and inorganic forms of NO_2^- and NO_3^-. In slaughterhouse wastewater, the nitrogen is available in organic form and NO_3^- in slaughterhouse wastewater it is typical of a stable form of nitrogen originated from decaying of biological organic matter (Yaakob *et al.*, 2018). Excessive NO_3^- levels in the slaughterhouse wastewater effluent possibly will lead to oxygen depletion due to the presence of harmful algae bloom and hence hindering watercourses (Mittal, 2004).

2.4.4 Suspended Solids

These are the insoluble and suspended matter found in wastewater and contain both inorganic and organic components. The degradation of organic material will finally be contributing to the BOD addition. High TSS in the slaughterhouse wastewater results in several environmental problems including the reduction of light penetration and transmittance, an increase of wastewater turbidity, inhabitance of the aquatic plant’s photosynthesis and cause suffocation to microbes due to absence of oxygen (Bilotta & Brazier, 2008).

2.5 Treatment of Slaughterhouse Wastewaters

To discharge the raw slaughterhouse wastewater into the receiving waters is unreasonable due to its high content of organic matter. The raw slaughterhouse wastewater requires intensive treatment before being discharged into the receiving waters. Different slaughterhouse wastewater treatment methods were deployed to achieve the required discharge limits into the environment as described below:

2.5.1 Preliminary Treatment

The solids and large particles generated during the slaughtering process are isolated from wastewater. The improvement of separation and collection of grease and foreign materials, grease traps may have a series of compartments. The preliminary treatment involves a series of treatment options, including screens and skimming chamber. Through the screens (coarse and fine), solid wastes are usually removed. Furthermore, the grease and oil from the slaughterhouse wastewater are separated from other wastes in the skimming chamber.

2.5.2 Physicochemical Treatment Methods

Depending on high organic load constituents of slaughterhouse wastewater, the effluent from preliminary treatment is allowed to pass through the primary or secondary treatment (physicochemical treatment methods). The physicochemical treatment methods encompass the separation of liquid and solids from slaughterhouse wastewater.

2.5.3 Biological Treatment

The biological treatment reduces the excessive environmental pollution indicators in the slaughterhouse wastewater by removing the soluble organic compounds that persist after primary treatment (Pierson & Pavlostathis, 2001). Generally, biological treatment is useful as a secondary treatment process in slaughterhouse processing facilities. This secondary treatment facility comprised the anaerobic and aerobic digestion units used in a combined process that relied on the slaughterhouse wastewater characteristics being treated (Arvanitoyannis & Ladas, 2008). Different biological treatment processes were used to treat the slaughterhouse wastewater as described below;

(i) Anaerobic Treatment

The effectiveness of treating a high strength slaughterhouse wastewater using anaerobic digestion is considered the preferred biological treatment method (Vidal *et al.,* 2019). In anaerobic treatment, the organic compounds are degraded using microbes into methane and carbondioxide. Besides of this treatment method, there is a complicated situation of the organic strength of slaughterhouse wastewater to attain the total stabilization of its compounds (Chan *et al.,* 2009). Therefore, anaerobically treated wastewaters typically require an extra post-treatment, constituents such as the Total Phosphorus, Total Nitrogen, pathogenic organisms, and organic matter are removed (Fig. 1; Chernicharo, 2006; Gomec & Yangin, 2010; Oliveira & Sperling, 2009).

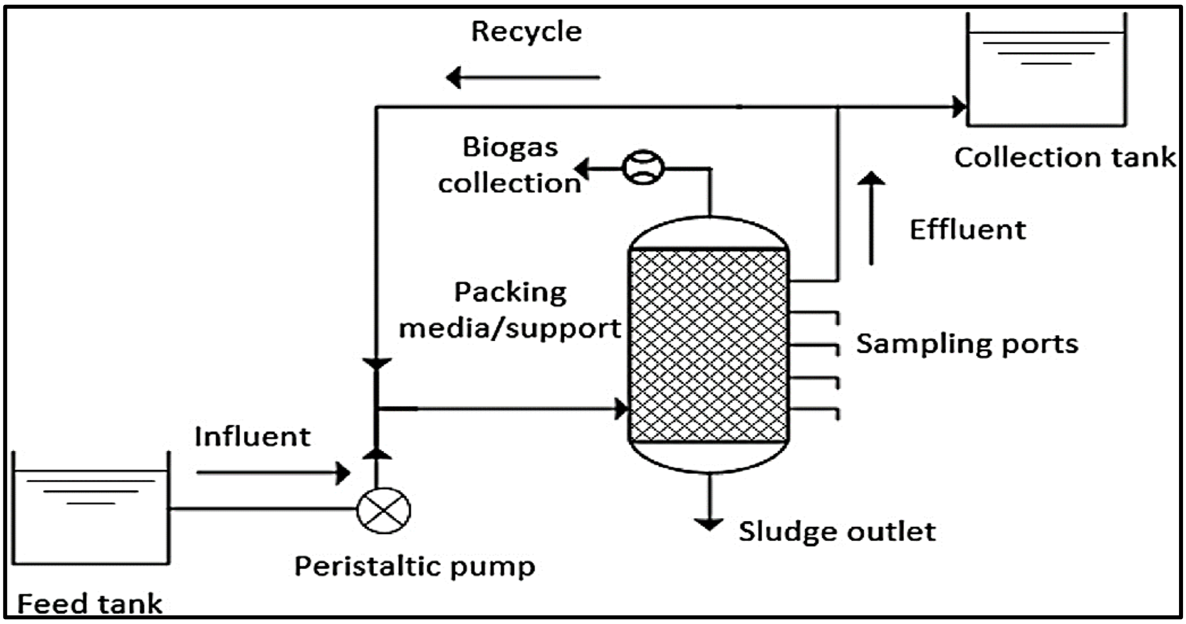

Figure 1: Schematic diagram of a representative of the anaerobic treatment system (Bustillo-Lecompte & Mehrvar, 2015)

(ii) Aerobic Treatment

The aerobic bacteria are accountable for the removal of organic matter in the existence of oxygen into the aerobic systems. The amount of oxygen required and treatment time increase abruptly depending on the strength of slaughterhouse wastewaters. The aerobic treatment is always used for final decontamination and removal of environmental pollution indicators from the slaughterhouse wastewater (Chernicharo, 2006).

(iii) Constructed Wetlands

Constructed wetlands are the smart alternative to conventional wastewater treatment and are the cost-effective method of biological treatment (Chan *et al.,* 2009; Oller *et al.,* 2011). The constructed wetland has small maintenance and operational costs, relatively little impacts on the environment and simplicity in design. The mechanisms of natural wetlands are simulated by constructed wetlands for combining biological, chemical and physical processes that occur when slaughterhouse wastewater, atmosphere, soil, microorganisms, and plants interact (García *et al.,* 2010). The constructed wetland is always used as a polishing unit for any wastewater treatment including slaughterhouse wastewater.

2.6 Biogas Production from Slaughterhouse Wastewater

Wastewaters produced from the meat industries can be processed through anaerobic digestion to produce biogas, and it may be converted to electricity or heat energy

(Abdeshahian *et al.,* 2016). An anaerobic digestion process is a reliable tool for producing clean energy sources, such as carbon dioxide and methane, known as biogas (Madsen *et al.*, 2011). Any organic matter can be processed with anaerobic digestion; digestion is the crucial factor in its successful treatability and biogas production (Khalid *et al.,* 2011).

The organic matter, for example, the creamy fat materials can support to improve the quality of the gas, provided that the magnitudes are reasonable and not too large to avoid acidity (Naik *et al.,* 2010). The acidity compounds (lactic acid) would be more easily assimilated by other organisms found in the anaerobic sludge (Martinez *et al.,* 2013). Furthermore, there are signs of propionic fermentation, which is carried out by the action of bacteria of the propionic bacterium type, fermenting lactic to propionic acid, acetic acid, CO_2 and water (Wang *et al.,* 2014). These break down the lactic acid into acetic acid and propionic acid, generating more raw material from which we obtain biogas (Menardo *et al.,* 2015).

Higher content of the liquid in the bioreactor results in a higher concentration of CO_2 dissolved in water and hence reducing the level of CO_2 in the gas phase (McCollom & Seewald, 2001). The higher temperature during the fermentation progression can lower the concentration of dissolved CO_2 in the slaughterhouse wastewater (Hendriks & Zeeman, 2009). Biogas' composition depends on the specific plant, feed composition and operating conditions of the anaerobic digesters (Scano *et al.,* 2014).

CHAPTER THREE

MATERIALS AND METHODS

3.1 Methods

The MCS wastewater treatment facility is located along Musoma Road, Mahina Ward, in Mwanza, Tanzania (Fig. 2). The location lies below the equator between latitudes 2° and 4° south and longitude between 32° and 35° east of Greenwich. The city of Mwanza is located at the southern shores of Lake Victoria and has a population of approximately four million; according to the national census of statistics, 2012.

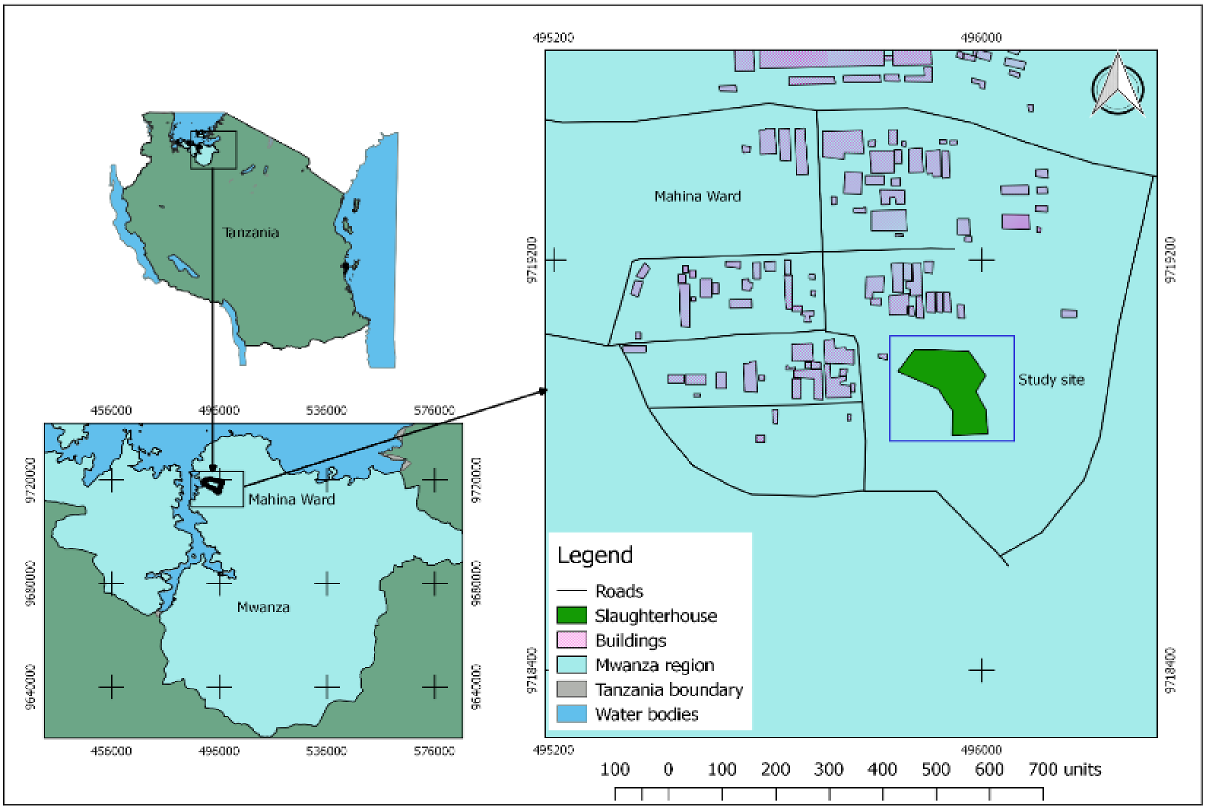

Figure 2: Map of Tanzania (top left corner) showing the location of Mwanza City (lower left) and a zoom-in of the Mwanza City Slaughterhouse facility

3.2 Treatment System Design

The system was designed to have the following parameters: Feed flow rate, Q = 65 m^3/h, the dimensions of batch stirred biodigester were: Diameter of 10 m, the total height of 8.50 m with water level height of 6.62 m, 1.38 m height of gas collector and 0.50 m was the free body space. The biodigester was designed to treat influent COD (4500 mg/L), BOD_5 (1200 mg/L), TSS (9700 mg/L) and NO_3^- (605 mg/L). It was designed for the anoxic process to involve the denitrification where nitrate was converted to NH_4^+ into the biodigester. The designed hydraulic detention time, τ was four days. The aeration tank has a diameter of 7 m and a height of 6.5 m with water level 6.0 m, aeration volume of 231 m^3, and designed hydraulic detention time, τ, of 1.8 days.

3.3 Wastewater Treatment at the Mwanza City Slaughterhouse

The MCS wastewater treatment facility is operated as a semi-batch system, providing an intermittent flow of wastewater into the plant's different units up to the constructed wetland (Fig. 3). The facility was designed to match its operations taking into account that slaughter activities usually happen between 3:00 and 6:00 a.m. The generated wastewater is quickly transferred into the biodigester to minimize biomethanation. Pumping into the biodigester is usually done for 1 to 2 h. The biodigester is fed from the bottom up. From the biodigester, the wastewater is transferred by gravity to be further treated in the aerated tank. Normally, aeration is done for 12 h, then stopped to allow the development of anoxic conditions for another 12 h. This mode of operation assists in the denitrification of NO_3^- produced in the aerator during the nitrification of ammonium. The aeration tank was designed to receive 85 mg/L of NH_4^+. Accordingly, the blower was designed to supply 48 kg/h of air for 12 h during the nitrification process.

After the aeration unit, there is a retention tank and a pump that continuously feeds the rest of the units. During fieldwork for the present study, the MCS wastewater treatment facility was receiving an average amount of wastewater of 32.7 m^3 per day from carcass and meat washing as well as the slaughterhouse floor cleaning due to a small number of animals slaughtered per day. Animals slaughtered at the MCS facility include goats, cattle and sheep. In the present study, the wastewater samples collected were found to contain large amounts of large solids from undigested intestinal materials. These were removed from the system using coarse and fine bar screens of 20 mm and 7.5 mm spacing at the preliminary treatment stage. The wastewater from the aeration tank was then transferred to the retention tank before being continuously pumped into the clarifier. The clarifier's role was to separate the solids from the aeration tank before the water entered the polishing step. The sludge accumulated in the clarifier was transferred into the sludge drying beds, later used as organic fertilizer for agricultural purposes. The dimensions of the sludge drying bed were: Area of 42 m^2, four (4) compartments each with a length of 3.75 m, the width of 3.75 m (which makes the total length of 16.5 m and width of 3.75 m), and height of 1.2 m. The inlet diameter channel was 100 mm terminating at 300 mm above the sand surface.

The clarifier's effluents were conveyed by gravity to the constructed wetland (CW), which was used as a polishing unit due to its ability to remove the remaining nutrients, organic matter, and suspended materials from wastewater. The constructed wetland was divided into two cells, each with dimensions of 30 m in length, 10 m width, and 1 m depth. The adequate treatment depth was 0.5 m, and granite gravel packing was of 20 mm size with a porosity of 0.4. The daily influent to each of the constructed wetland cells arranged in parallel was around 16 m^3. During the present study, the constructed wetland was observed to have a retention time of around 3.3 days. Also, the type of plants used in the CW system was the *Cyperus papyrus sp.*

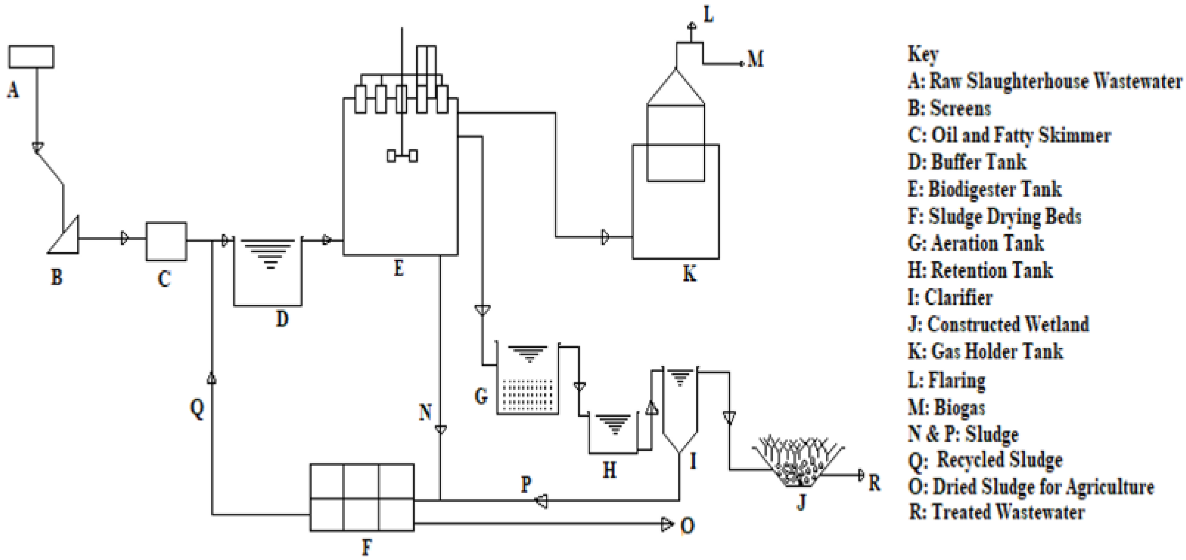

Figure 3: Treatment scheme of Mwanza City Slaughterhouse wastewater

3.4 Onsite Measurements

Onsite measurements for EC, pH, TDS, temperature, and DO was carried out using a multiparameter probe (Palintest MACRO 900). Wastewater turbidity was measured using a turbidimeter (Palintest 09011150103). Wastewater and biogas volumes were recorded daily using a mass flow totalizer (GFT-110A). Biogas production was recorded daily, whereas biogas composition was analyzed weekly. Biogas composition was determined using a gas analyzer (Geotech BIOGAS 5000). The facility’s power consumption was determined using an electrical meter (EDMI EUPR-1232-1100) and a sub-meter (EM 0026-JC).

3.5 Wastewater Sample Collection

The daily amount of slaughterhouse wastewater produced at the MCS facility required treatment before discharging into the aquatic environment. In the present study, the analysis of influent and effluent wastewater was done. The sampling and analysis were done for five months. The performance evaluation period was started after two months of the trial runs, where the plant performance observed (Table 1). In this period, a total of 112 samples were taken and analyzed. Duplicate wastewater samples for influent and effluent of each treatment unit were collected in 500 mL plastic bottles. After collection, the samples for COD, NH_4^+, NO_3^- and NH_3 analysis was acidified by sulfuric acid to a pH below 2 to inactivate microbial activities. In contrast, another sample was not acidified as they could be transferred to reach the NM-AIST laboratory within 24 h while packed into an ice-packed cool box kept at a temperature below 4 °C.

3.6 Laboratory Analysis

The analysis of NH_4^+, NO_3^- and NH_3 were done using a spectrophotometer (Hach DR-2800™). The analysis of NH_3 and NH_4^+ using Nessler method (Jeong *et al.,* 2013). The analysis of NO_3^- was done using the cadmium reduction method. The COD was determined using a HI-839800 Thermo-Reactor (HANNA Instruments). These parameters were analyzed as per standard methods for examinations of water and wastewater (APHA, 2012). Titration method was used to measure the soluble volatile fatty acids (VFAs) and alkalinity in the biodigester. The analysis of a five-day BOD was determined through incubation (OxiTop® IS12). The TSS was determined at a temperature of 105 °C in a drying oven (BINDER GmbH FD 56 E3). The total volatile solids (TVS) and volatile suspended solids (VSS) were quantified following standard methods at a temperature of 550 °C inside a muffle furnace (Cole-Parmer Stable Temp 1100 °C Box Furnace: CBF Series). The weight of dry solid samples was determined using a weighing balance (CY 204 S/N 15201586). Filtration of the slaughterhouse wastewater was done using a filtration pump (WELCH 2546C-02B) combined with a conical flask (Pyrex 580913 PORO 3). The faecal coliform count was determined in triplicates where the Petri-dishes of MacConkey agar containing 0.1 mL sample on filters (11406 ø 47 AC 1502023 0.45) were inoculated and incubated at 44.5 °C for 24 h before counting.

3.7 Data Analysis

The data obtainedwere analyzed using Excel, OriginPro 9.0 App, R-Studioand Geographical Information System as computer application software.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 General Operational Conditions

The present study was carried out for a period of five months, from February to June 2019. A total of 112 wastewater samples were collected and analyzed. The daily amount of wastewater fed into the biodigester at the MCS was averaged to 32.7 m^3. This amount of slaughterhouse wastewater produced through animal slaughter and related activities was but a fraction of the design value of 130 m^3 per day. The difference is attributed to the lower number of animals being slaughtered per day than the design capacity. The design capacity was for the facility to slaughter about 750 animals per day. During the present study, only about 250 animals were being slaughtered per day. The effluent from the biodigester and clarifier was fed into the retention tank with a holding capacity of 130 m^3 per day installed with a pump that continuously fed the clarifier and the constructed wetland at a rate of 5.42 m^3/h.

Wastewater temperature, pH and dissolved oxygen were measured onsite (Table 3). The present study observed that the MCS wastewater treatment facility was operating at around 26.3 ± 0.3 °C. This ambient temperature was lower than the one recommended in other studies i.e., a mesophilic temperature ranging from 30 to 40 °C for essential enhancement of treatment efficiency as well as biogas production (Tsegaye *et al.*, 2018). The treatment efficiency of the MCS bioreactor can be significantly improved by raising this temperature using solar heating (Kakaç & Pramuanjaroenkij, 2016) or using part of the biogas generated to heat the incoming wastewater before entering the biodigester. At the time of the present study, improvements were not possible; however, this has remained a recommendation for further improvement.

The present study also observed that the MCS wastewater treatment facility operated at a pH of approximately 7.2 ± 0.1 that was within the optimal range for the bioreactors and is usually controlled by the VFA-to-alkalinity ratio. A pH range of 6.5 to 8.0 is known not to inhibit methanogenic bacteria during biogas production (Reis *et al.,* 2016).

The DO concentrations ranged from 0.29 to 3.82 mg/L (Table 2). The DO values of 0.29, 0.24, 3.82 and 1.79 mg/L were recorded in the buffer tank, biodigester outlet, aeration tank and constructed wetland. In comparison, the anticipated design DO values were 0.21, 5.0 and

2.0 mg/L for the buffer tank, aeration tank and constructed wetland, respectively. Compared with the anticipated 5 mg/L, the low DO in the aeration tank was probably due to lower air supply from the blower of around 41 kg/h than the anticipated supply of air of 48 kg/h.

The DO in anaerobic digesters may be caused by factors such as high mixing rates, high recirculation rate, and too much loss of activated sludge (Botheju & Bakke, 2011; Kato *et al.*, 1997). Conklin *et al.* (2007) studied the influence of DO on anaerobic digestion processes and found that a supply of 3 to 4 mg/L of DO led to 27% of active methanogenesis. These researchers concluded that short-term oxygen exposure did not significantly reduce methanogen activity. However, continuous oxygen exposure was found to affect the methanogenic biomass activity negatively. Despite the negative influence of oxygen exposure, researchers found no effect on long-term digester performance in terms of the biogas production rate. Therefore, for the MCS facility, it is essential to monitor DO loadings into the digester to improve the long-term methanogen activity of the facility.

Table 3: Physico-chemical operational conditions for Mwanza City Slaughterhouse wastewater treatment system

Parameter measured	Maximum	Minimum	Mean (± SD)
Temperature, T (°C)	26.7	25.9	26.3 ± 0.3
pH	7.4	7.1	7.2 ± 0.1
Dissolved Oxygen, DO (mg/L)	3.82	0.24	2.0 ± 0.4

4.2 The effect of Agitation on Biogas Production

The effects of agitation time on the biodigester was investigated for zero to 6 h of agitation. The effects of biodigester agitation duration and influent wastewater volume on the amount of biogas produced at the MCS wastewater treatment facility have been indicated (Table 4). Each of the agitation time was run once per day for 7 days and biogas produced during that period was recorded daily. With no agitation in the system and when the average volume of feed was 23 m^3/day, the biogas produced was 145 m^3 per day. With one hour of constant agitation and an average influent feed of 20 m^3 per day, about 230 m^3 of biogas was produced. Increasing the hours of agitation to two at an average influent feed of about 19 m^3 per day, continued to lower the volume of biogas produced. Similarly, when agitation time was increased to four hours at an influent volume of about 22 m^3 per day, a dramatic reduction in biogas production was observed. A further increase in the number of agitation hours to six at an influent volume of about 22 m^3, resulted in a further decrease in biogas production. Thus, the best biogas production occurred when the agitation time of 1 h was applied. It should be noted that before the start of the present study, the biodigester used to be agitated for 4 h per day. The agitation time of 1 h at a rate of 30 rpm was therefore, recommended for improved biogas production. Agitation duration and speed have been linked to biogas production in a previous study (Aworanti *et al.,* 2017). Other researchers have also found that a gentle biodigester agitation distributes the substrates uniformly to form a uniform suspension of solid and liquid parts, prevents foam formation, and improves biogas production through fermentation processes (Lemmer *et al.,* 2013).

Table 4: The combined effect of agitation time and influent wastewater volume on biogas production at the Mwanza City Slaughterhouse wastewater treatment facility

Agitation (h)	Slaughterhouse wastewater conveyed into biodigester (m^3)	Biogas production (m^3)
0	23 ± 1.5	145.2 ± 12.4
1	20 ± 2	231.7 ± 9.6
2	18.9 ± 1.4	185.6 ± 10.3
4	22.1 ± 3.0	152.4 ± 9.7
6	21.7 ± 2.1	149.3 ± 9.1

4.3 Biodigester Unit Performance

The biodigester performance for the removal of critical environmental pollutants has been indicated (Table 5). Transformation of N and N-compounds and related mass balance explanations are found in Equations 1 to 5 below:

Alkalinity within an acceptable level is known to favour biogas production through the maintenance of pH (Jung *et al.,* 2019; Prabhudessai & Mutnuri, 2013). An acidic environment in the biodigester is inhibitive in biogas production (Lee *et al.,* 2019; Sakar *et al.*, 2009). Thus, for optimal biogas production, maintenance of alkalinity as $CaCO_3$ within a favourable range is essential. The Ammonium and alkalinity can be expected to increase in a well-performing wastewater treatment system as a result of protein breakdown to NH_3, which further combines with CO_2 to form $NH_4(HCO_3)$ (Equation 1) (Sunirat, 2016). Likewise, for well-performing wastewater treatment systems, the VFAs should be expected to decrease in the biodigester because they become consumed by the methanogens in the methanogenic phase. However, in the present study, the alkalinity level decreased. At the same time, the VFAs increased with time, indicating poor performance in the treatment system, which might be attributed to many factors such as retention time and agitation frequency, to mention a few. The VFAs-to-alkalinity ratio during the process increased from 0.13 to 0.3 (Table 5), which indicates that the increase of VFAs overloaded the buffering system. However, the VFA-to-alkalinity ratio under the present study was still in the acceptable range as per Shujun *et al.* (2015). They indicated that for a well-working digester, the VFA-to-alkalinity ratio falls between 0.3 to 0.4.

$$NH_3 + H_2O + CO_2 \rightarrow NH_4(HCO_3) \quad (1)$$

In the present study, at pH values of 7.2 the NH_3 to NH_4^+ the ratio was about 0.5 (Table 5). This was consistent with a recent study investigating ammonia levels in the liquid phase during anaerobic digestion (Mutegoa *et al.*, 2020). In wastewaters, ammonia exists, primarily, in two forms: The charged ammonium ion and the uncharged aqueous ammonia. This coexistence is highly pH- and temperature-dependent. The uncharged ammonia component is more toxic than its charged counterpart because of its lipophilicity and ability to traverse biological membranes. At a pH range between 7 and 12 both the charged and uncharged species of ammonia are known to exist in wastewater at varying percentages (Caicedo *et al.*, 2000; Körner *et al.*, 2001; Philippe *et al.*, 2011). Dissolved uncharged ammonia increases with increasing pH and temperature. At pH below 7, virtually, all ammonia is expected to exist as soluble ammonia gas. In the present study, at a pH of 7.2, the measured ammonia concentration was higher than expected and could be considered inhibitive. The cause of this high ammonia concentration is unknown. However, a study by Jeong *et al.* (2013) pointed out the deficiency of titrimetric methods in estimating ammonia species concentration in wastewater, especially when 'hindering' ions such as Mg, Cl and Fe are present in high concentrations. In the present study, NH_3 was overestimated due to that there were no apparent toxicity indications in the system, as evidenced by the amount of biogas produced. Thus, a recommendation is made for a further study to examine the causes of the reported high concentration of ammonia.

A relatively high i.e. > 60% removal efficiency was achieved in the biodigester unit for BOD_5, COD, TSS, nitrate and turbidity (Table 5). The high COD removal efficiency could be due to the biodigester's capacity to remove chemical contaminants through treatment processes and settleable sludge. As de Mes *et al.* (2003) reported, for cow slurry, the soluble COD of 25% inside the biodigester could be converted into biogas due to increased circulation of water forming, a well-settleable sludge. In the present study, the composition of biogas resulting from COD transformation was as follows: Methane (70.3%), carbon dioxide (29.2%) and other gases (0.5%). In the biodigester, there was a net production of NH_4^+. This situation may be attributed to the biodigester's anoxic conditions, which led to the net formation of NH_4^+ through dissimilatory reduction of NO_3^- to form NH_4^+ and the anoxic fermentation of organic N to form NH_4^+ (Behrendt, 2014) (Equations 2 - 3). An increase in NH_4^+ concentration in the biodigester resulted from hydrolysis of N-containing organic matter (Equation 2). In dissimilatory nitrate reduction, the resultant NH_4^+ will be taken up by microorganisms for their growth. Anaerobic condition (hydrolysis/ammonification anoxic condition is detrimental to anaerobic processes. Rather, NH_4^+ will be passed with the effluent into the aeration tank.

$$\text{Organic N} \xrightarrow{\text{Fermentation}} NH_4^+ \tag{2}$$

$$NO_3^- \xrightarrow{\text{Dissimilatory}} NH_4^+ \tag{3}$$

In Table 4, it is indicated that NO_3^- was still high in the biodigester. In the present study, it was observed that biodigester agitation was done intermittently. Agitation about the volume of the wastewater in the digester might have favoured nitrification process thus increasing the concentration of NO_3^- in the system. Due to this intermittent agitation, there was an improper separation of solids. Improper separation of solids may have led to increased formation of NO_3^- in the biodigester. The sources of NH_4^+ vary, including the hydrolysis of urea (Equation 4) and undigested protein degradation; the latter source is slow and of secondary importance. Ammonium is further transformed to nitrite and nitrate by autotrophic microorganisms, as indicated in Equation 5. During the transformation of NH_4^+ into nitrite, a greenhouse gas i.e. N_2O is usually formed as an intermediate (Sommer *et al.*, 2006). The formation of nitrous oxide has thus raised considerable interest in the study of nitrification.

$$CO(NH_2)_2 + 3H_2O \rightarrow 2NH_4^+ + HCO_3^- + OH^- \tag{4}$$

$$NH_4^+ \xrightarrow{\text{Primary nitrifiers}} NO_2^- \xrightarrow{\text{Nitrobacters}} NO_3^- \tag{5}$$

The biodigester treatment processes were energy-positive, involving simple mechanisms shown in Equations (2) to (5). The expected design and actual performance of the biodigester were satisfactory (Table 5) because, for all parameters, the actual efficiency was lower than the design by an error margin of < 15%. Despite these discrepancies in performance, UASB systems, such as those investigated in the present study, are increasingly becoming a promising technology for treating slaughterhouse wastewaters with reported efficiencies ≥ 84%, ≥ 77% and ≥81% for BOD_5, COD and TSS, respectively (Mittal, 2006). This implies that the efficiency of the studied biodigester can be further improved.

Table 5: Performance of the biodigester for removal of key environmental contaminant

Performance parameter	**Influent**	**Effluent**	**Expected design efficiency (%)**	**Actual Biodigester efficiency (%)**
BOD_5 (mg/L)	960 ± 159	320 ± 27	71.7	66.7
COD(mg/L)	4032 ± 624	1312 ± 86	78	67.5
TSS (mg/L)	10100 ± 428	2860 ± 104	60.1	71.7
NH_4^+ (mg/L)	189 ± 14	550 ± 18	-145	-191.0
NH_3 (mg/L)	570 ± 85	315 ± 58	32.0	44.7
NO_3^- (mg/L)	307.5 ± 9.5	82.9 ± 10.7	70.9	73.0
Fecal coliform (CFU/100 mL)	37667 ± 1058	19333 ± 482	45.2	48.7
Turbidity (NTU)	17600 ± 373	4020 ± 144	70.5	77.2
Alkalinity as $CaCO_3$ (mg/L)	76.8 ± 2.7	66.4 ± 2.8	17.2	13.5
VFAs as acetic acid (mg/L)	9.7 ± 0.26	22.7 ± 1.9	13.8	-133.5

4.4 Aeration Tank Performance

The aeration tank (AT) performance in terms of percentage removal for COD (52.4%), BOD_5 (51.6%), TSS (63.6%), NH_4^+ (36.7%), faecal coliform (46.6%), NO_3^- (58.3%), NH_3 (66.5%) and turbidity (66.9%) has been given (Table 6). The aeration system was run for 12 h a day. Compared to the biodigester (Table 5), the aeration tank consumed the influent NH_4^+ (Table 6). The aeration tank influent NH_4^+ was oxidized to NO_2^- and NO_3^- in the system using *Nitrosomonas* and *Nitrobacter* bacteria, respectively. Furthermore, the denitrification processes during no-aeration hours may have caused significant removal of nitrate (Li, 2010). In the aeration tank, treatment processes took place in a linear manner (Equations 5-8). Equations (5) and (6) show the processes during the 12 h of aeration. In Equations (7) and (8), ammonia was acidified using microbes through denitrification processes in the other 12 h of the day when there was no aeration.

$$NH_4^+ \xrightarrow{\text{Assimilation}} NO_2^- \quad (5)$$

$$NO_2^- \xrightarrow{\text{Assimilation}} NO_3^- \quad (6)$$

$$NH_3 + \tfrac{3}{2}O_2 \xrightarrow{\text{Nitrosomonas}} HNO_2 + H_2O + \text{Biomass} \quad (7)$$

$$HNO_2 + \tfrac{1}{2}O_2 \xrightarrow{\text{Nitrobacter}} HNO_3 + \text{Biomass} \quad (8)$$

In comparison to design, removal efficiencies in the aeration step were satisfactory (Table 6) as most removal efficiencies of each parameter except COD were better or within 10% error. The COD removal had a 20% error.

Table 6: Performance of the aeration tank (AT) for removing the key environmental pollutants

Measured parameter	Influent	Effluent	Expected design efficiency (%)	Actual AT efficiency (%)
BOD_5 (mg/L)	320 ± 27	155 ± 23	56.4	51.6
COD (mg/L)	1312 ± 86	624 ± 81	66.1	52.4
TSS (mg/L)	2860 ± 284	1040 ± 154	60.5	63.6
NH_4^+ (mg/L)	550 ± 18	285 ± 6	29.4	48.2
Fecal coliform (CFU/100 mL)	19333 ± 482	10324 ± 273	38.9	46.6
NO_3^- (mg/L)	82.9 ± 10.7	34.6 ± 6.8	56.2	58.3
NH_3 (mg/L)	315.0 ± 58	105.5 ± 12.8	63.1	66.5
Turbidity (NTU)	4020 ± 144	1934 ± 96	56.7	51.9

4.5 Constructed Wetland Performance

Compared to the initial two-month performance (Table 1), the CW achieved better removal efficiencies after the five months of study (Table 6). At the beginning of the present study, it was observed that plants (*Cyperus papyrus sp.*) were not well established in the CW. This may have led to low performance in contaminant removal from wastewater. Also, it was observed that after a well-established growth of such plants in the CW, there was a remarkable improvement in the removal of faecal coliform, organics, and nutrients from slaughterhouse wastewater (Table 6). Microbes and plant roots are capable of removing organic compounds under both aerobic and anaerobic conditions. The microbiology of the slaughterhouse wastewater is delicate and intricate, involving several bacterial groups, each with its optimum working conditions. The microbes in the CW were sensitive to some process parameters, including alkalinity, pH, VFAs, temperature, etc. Thus, in the present study, these process parameters either controlled plant-related ecological functions or inhibited specific bacterial groups. Various plant and microbial processes are known to stabilize soils, vegetation, and other assemblages in the CWs. They could indeed support the reduction of nutrients and pathogens in the slaughterhouse wastewater (Vymazal, 2010). Operational processes in the constructed wetland are expressed in Equation 9;

$$\text{Organic Carbon} + O_2 \xrightarrow{\text{Heterotrophs}} CO_2 + \text{Biomass} \qquad (9)$$

The two compartments of the CW were designed to treat 65 m^3 of wastewater per day. In the present study, the CW was observed to treat 42 m^3 of wastewater volume per day. The expected effluent quality levels were: COD (60 mg/L), BOD_5 (30 mg/L), TSS (100 mg/L) and NO_3^- (20 mg/L). The constructed wetland's actual performance was excellent because the maximum error of the actual efficiencies was close to 2% compared to the design efficiencies (Table 6). Other studies on the slaughterhouse wastewater using CWs provided similar results (Paschal *et al.*, 2017; Vymazal, 2010). A study conducted in Uganda revealed that a CW could efficiently remove the following contaminants: COD (71%), BOD (71%) and NO_3^- (76%) (Odong *et al.*, 2013). In the present study, the CW removed the measured contaminants with > 78% (Table 6).

Table 7: Performance of the constructed wetland (CW) in the removal of the environmental pollutants

Measured parameter	**Influent**	**Effluent**	**Expected design efficiency(%)**	**Actual CW efficiency (%)**
BOD_5 (mg/L)	155 ± 23	25 ± 3	85.2	83.9
COD (mg/L)	624 ± 81	68 ± 9	75.9	78.2
TSS (mg/L)	1040 ± 154	40 ± 6	97.2	96.2
NH_4^+ (mg/L)	285 ± 6	5 ± 1	99.1	98.2
Fecal coliform (CFU/100 mL)	10324 ± 273	330 ± 15	97.2	96.8
NO_3^- (mg/L)	34.6 ± 6.8	7.4 ± 2.1	80.3	78.6
NH_3 (mg/L)	137.5 ± 12.8	5 ± 1	97.6	96.4
Turbidity (NTU)	1934 ± 96	12.5 ± 1.2	99.1	99.4

4.6 Performance of the Integrated System

The overall performance of the biodigester-constructed wetland system has been provided (Table 8). The present study shows that the integrated biodigester-CW system performed well in the removal of COD (98.3%), BOD_5 (97.4%), TSS (99.6%), NH_4^+ (138.1%), faecal coliform (99.1%), NO_3^- (93.3%), NH_3 (99.1%) and turbidity (99.9%). Levels of NH_3 and NO_3^- were reduced at the aeration stage by the nitrification and denitrification processes, respectively. It could be that the good performance of the biodigester-CW system was due to the presence of intermediate units which were performing complementary treatment tasks. Previous research found that good bioreactor operations for soluble COD removal were attributed to variations of solids settling in slaughterhouse wastewater (Manjunath *et al.*, 2000). The MCS treatment system was designed to remove 99%, 98%, and 73% of COD, BOD_5 and NO_3^-, respectively. The combined biodigester-CW system of the MCS wastewater treatment facility was able to remove all contamination indicators with an efficiency of > 97% and produced effluents quality that fell within the TBS limits (Table 8).

Table 8: Overall performance of the integrated biodigester-constructed wetland for removal of environmental pollutants

Measured Parameter	Influent	Effluent	Allowed TZS limits	Expected design efficiency (%)	Overall efficiency (%)
BOD_5 (mg/L)	960 ± 159	25 ± 3	30	98.2	97.4
COD (mg/L)	4032 ± 624	68 ± 9	60	99.1	98.3
TSS (mg/L)	10100 ± 428	40 ± 6	100	99.2	99.6
NH_4^+ (mg/L)	189 ± 14	5 ± 1	10	98.6	97.4
Faecal Coliform (CFU/100 mL)	37667 ± 958	330 ± 15	1000	98.7	99.4
NO_3 (mg/L)	307.5 ± 9.5	7.4 ± 2.1	50	96.4	97.6
NH_3 (mg/L)	570 ± 23	5 ± 1	N.I	98.9	99.1
Turbidity (NTU)	17600 ± 373	12.5 ± 1.2	300	99.2	99.9

N.I.* = Not indicated in the standards

Furthermore, the MCS wastewater treatment facility was designed to produce sludge volume of about 19400 and about 5700 m^3 per year from the biodigester and aeration tanks, respectively. In the present study, the MCS facility was found to produce a sludge volume of 6580 m^3 and 2205 m^3 in five months of this studyfrom the biodigester and aeration tanks, respectively. Sludge produced at the MCS facility is usually managed in the sludge drying bed and then applied as fertilizer to boost plant production at nearby agricultural fields.

4.7 Biogas Production

In the present study, the average biogas production at the MCS facility was 158.2 m^3 per day. This high biogas production was probably caused by the presence of organic materials required for anaerobic bacteria as substrates for methanogenesis processes. The substrates present in the slaughterhouse wastewater are known to have adequate nutritional requirements for anaerobic bacteria to form new cells and act as energy sources (Anahita *et al.,* 2019). Degradation of organic materials in the MCS biodigester to produce biogas can be attributed to the consortia of anaerobic bacteria under favourable conditions (Shah *et al.*, 2017). Also, factors such as favourable pH, temperature, and VFA-to-alkalinity ratio are known to stimulate the anaerobic bacteria to digest the liquid and cellulosic material in the slaughterhouse wastewater during the fermentation process (Jain *et al.*, 2015).

4.8 Energy Consumption

The electrical energy consumption for MCS wastewater treatment facility was observed to range between 50 and 65 kWh per day. Energy-consuming activities included the feeding of slaughterhouse wastewater into the digester, agitation of the biodigester, running of the aeration system, clarifier feeding and facility lighting. The present study found that these activities consumed electricity up to 1950 kWh per month. This amount of energy was sometimes too costly for the MCC to afford and failed the continuity of operations at the treatment facility. However, the amount of biogas produced per day by the MCS wastewater treatment facility, if converted to electricity, would be enough to power the facility (Fig. 4; Uddin *et al.*, 2016) reported that 2.5 kWh electrical energy can be generated from one cubic meter of biogas. Therefore, the daily biogas produced at MCS can satisfy the plant's power requirements if converted to electricity using a biogas-run generator.

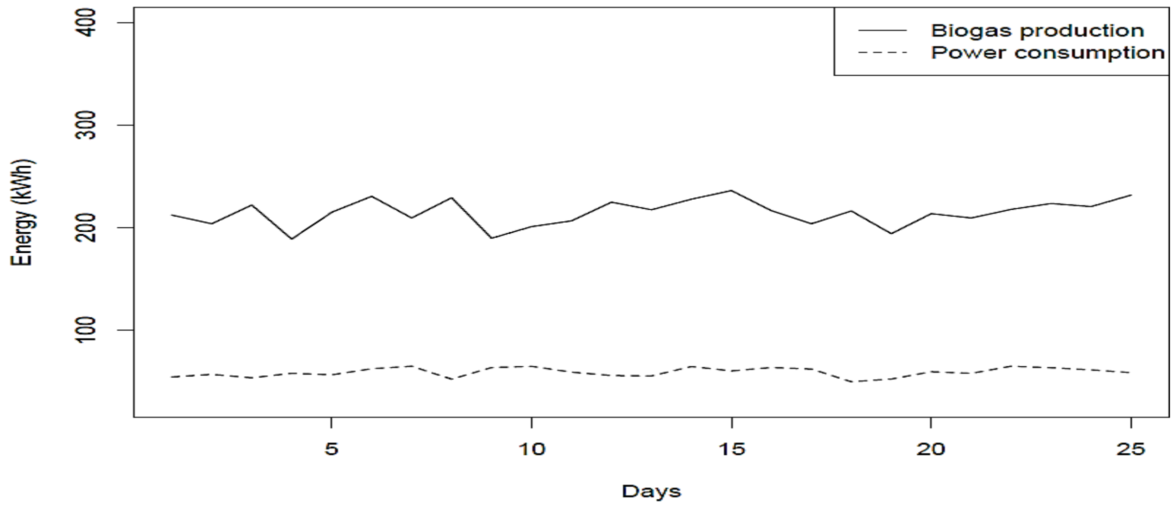

Figure 4: Relationship between energy consumption and the Mwanza City Slaughterhouse wastewater treatment facility's biogas production in 25 days of a month. Daily biogas volume produced was converted into electrical energy (kWh)

4.9 Biogas Composition

The average biogas composition was as follows: CH_4 (70.3%), CO_2 (29.2%), O_2 (0.5%) and other gases of NH_3 (130 ppm) and H_2S (120 ppm) per day (Table 9). Usually, biogas composition is dependent on the feedstock type and the activity of the consortia of anaerobic bacteria involved in the digestion process. The usual biogas composition from anaerobic digestion of organic-rich substrate includes CH_4 (50–75%), CO_2 (25–45%), O_2 (0–2%), NH_3 (0-1%) and H_2S (0-1%) (Shah *et al.,* 2017). Generally, the MCS wastewater treatment facility produced a high amount of biogas. However, the facility has more biogas production potential than it was producing during the present study. The quantity and quality of biogas produced would be enough to stand as a source of energy for the facility.

Table 9: Composition of the biogas produced at the Mwanza City Slaughterhouse wastewater treatment facility

Parameter	Biogas composition
CH_4 (%)	70.3 ± 1.9
CO_2 (%)	29.2 ± 1.7
O_2 (%)	0.5 ± 0.3
NH_3 (ppm)	130 ± 2
H_2S (ppm)	120 ± 1

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

Slaughterhouse wastewater treatment is still a challenge not only to countries in sub-Saharan Africa but also in other developing countries. To reduce the energy challenges in the present study, it was recommended that the MCC should invest in an energy conversion system to benefit from the biogas produced. The MCC should also consider installing a heating system, which utilizes the excess heat from the conversion of biogas to electricity to heat the feedstock into the biodigester. This will result in better performance of the system and increased gas yield. Furthermore, the influent should be fed at a flow rate of 65 m^3/h in the integrated biodigester-CW may be changed to 5.24 m^3/h to provide a continuous flow into the facility and maintain its operational processes throughout the day.

In the present study, the biodigester's gentle agitation at 1 to 2 h in a day was found to yield maximum biogas of about 185 to 231 m^3. This estimated amount of biogas would be enough to run the MCS wastewater treatment facility operations with surplus energy that can be supplied to the nearby users at a relatively affordable cost.

Aeration was done for 12 h to allow nitrification process, then stopped to allow the development of anoxic conditions for another 12 h. These conditions were observed as the optimal operating conditions since previously the aeration was done 4 h in a day in the aeration tank.

5.2 Recommendations

(i) The MCC should invest in an energy conversion system to benefit from the biogas produced by installing the generator to convert the available energy (biogas) into electricity.

(ii) Treatment efficiency of the MCS bioreactor can be significantly improved by raising the operating ambient temperature either using solar heating or through using part of the biogas generated to heat the incoming wastewater before entering the biodigester.

(iii) In the present study, NH_3 and NO_3^- were overestimated due to that there were no apparent toxicity indications in the system as evidenced by the amount of biogas produced. To this point, a recommendation is thus made for a further study to examine the causes of the reported high concentration of ammonia.

REFERENCES

Abdeshahian, P., Lim, J. S., Ho, W. S., Hashim, H., & Lee, C. T. (2016). Potential of biogas production from farm animal waste in Malaysia. *Renewable Sustainable Energy Reviews*, *60*, 714-723. https://doi.org/10.1016/j.rser.2016.01.117

Abdurahman, N. H., Rosli, Y. M., Azhari, N. H., & Bari, H. A. (2015). The potential of ultrasonic membrane anaerobic systems in treating slaughterhouse wastewater. *Journal of Water Reuse and Desalination*, *5*(3), 293-300. https:// doi. org/ https:// doi.org 10.2166/ wrd.2015.107

Ahmadian, M., Yousefi, N., Van Ginkel, S. W., Zare, M. R., Rahimi, S., & Fatehizadeh, A. (2012). Kinetic study of slaughterhouse wastewater treatment by electrocoagulation using Fe electrodes. *Water Science Technology*, *66*(4), 754-760. https:// doi. org/ 10. 2166/wst.2012.232

Amorima, I. R. D., & Nery, D. (2007). Water conservation and effluent minimization: Case study of a poultry slaughterhouse. *Resources, Conservation and Recycling*, *51*(3), 93–100. https://doi.org/10.1016/j.resconrec.2006.08.005

Anahita, R., Saad, A., Yaser, D., & Elsayed, E. (2019). A Review on Anaerobic Co-Digestion with a Focus on the Microbial Populations and the Effect of Multi-Stage Digester Configuration. *Energies*, *12*(6), 1106. https: // doi. org/ https: /doi. org/ 10.3390/ en12061106

APHA/AWWA/WEF (2012) *Standard Methods for the Examination of Water and Wastewater* (22^{nd} Ed.). American Public Health Association/American Water Works Association/Water Environment Federation http: //yabesh. ir/ wp-content/ uploads/ 2018/02/ Standard-Methods-23^{rd} Perv.pdf

Arvanitoyannis, I. S., & Ladas, D. (2008). Meat waste treatment methods and potential uses. *Institute of Food Science and Technology*, *43*(3), 543-559. https: //doi. org/ https: //doi.org/10.1111/j.1365-2621.2006.01492.x

Aworanti, O. A., Agarry, S. E., & Ogunleye, O. O. (2017). Biomethanization of Cattle Manure, Pig Manure and Poultry Manure Mixture in Co-digestion with Waste of Pineapple Fruit and Content of Chicken-Gizzard-Part I: Kinetic and Thermodynamic

Modelling Studies. *The Open Biotechnology Journal*, *11*(1), 36-53. https: //doi. org/ https:doi.org/10.2174/1874070701711010036

Aziz, A., Basheer, F., Sengar, A., Irfanullah, S. U., & Farooqi, I. H. (2019). Biological wastewater treatment (anaerobic-aerobic) technologies for safe discharge of treated slaughterhouse and meat processing wastewater. *Science of The Total Environment*, *686*, 681-708. https://doi.org/https://doi.org/10.1016/j.scitotenv.2019.05.295

Bazrafshan, E., Mostafapour, F. K., Farzadkia, M., Ownagh, K. A., & Mahvi, A. H. (2012). Slaughterhouse wastewater treatment by combined chemical coagulation and electrocoagulation process. *Plos One*, *7*(6). https: //doi. org/ 10.1371/ journal. pone. 0040108

Behrendt, A. (2014). *Competition between dissimilatory nitrate reduction to ammonium and denitrification in marine sediments* [Dissertation, Staats-und Universitätsbibliothek Bremen]. http://elib.suub.uni-bremen.de/edocs/00104464-1.pdf

Bilotta, G., & Brazier, R. (2008). Understanding the influence of suspended solids on water quality and aquatic biota. *Water Research*, *42*(12), 2849-2861.

Botheju, D., & Bakke, R. (2011). Oxygen effects in anaerobic digestion: A review. *The Open Waste Management Journal*, *4*(2011), 1-19. https:// openarchive. usn. no/ usn-xmlui/ bitstream/ handle/11250/2438503/BothejuBakke.pdf?sequence=2&isAllowed=y

Bustillo-Lecompte, C. F., & Mehrvar, M. (2015). Slaughterhouse wastewater characteristics, treatment, and management in the meat processing industry: A review on trends and advances. *Journal of Environmental Management*, *161*, 287-302. https: //doi. org/ https: //doi.org/10.1016/j.jenvman.2015.07.008

Bustillo-Lecompte, C. F., & Mehrvar, M. (2015). Slaughterhouse wastewater characteristics, treatment, and management in the meat processing industry: A review on trends and advances. *Journal of Environmental Management*, *161*, 287-302. https: //doi. org/ https:/ /doi. org/10.1016/j.jenvman.2015.07.008

Caicedo, J. R., Van Der Steen, N. P., Arce, O., & Gijzen, H. (2000). Effect of total ammonia nitrogen concentration and pH on growth rates of duckweed (*Spirodela polyrrhiza*). *Water Research*, *34*(15), 3829-3835.

Caixeta, C. E., Cammarota, M. C., & Xavier, A. M. (2002). Slaughterhouse wastewater treatment: Evaluation of a new three-phase separation system in a UASB reactor. *Bioresource Technology*, *81*(1), 61-69. https: //doi. org/ 10.1016/ S0960-8524(01)00070-0

Chan, Y. J., Chong, M. F., Law, C. L., & Hassell, D. G. (2009). A review on anaerobic–aerobic treatment of industrial and municipal wastewater. *Chemical Engineering Journal*. https://doi.org/https:/doi.org/10.1016/j.cej.2009.06.041

Chernicharo, C. A. L. (2006). Post-Treatment Options for the Anaerobic Treatment of Domestic Wastewater. *Environmental Science and BioTechnology*, *5*, 73-92. https://doi.org/10.1007/s11157-005-5683-5

Conklin, A., Bucher, R., Stensel, H. D., & Ferguson, J. (2007). Effects of oxygen exposure on anaerobic digester sludge [Article]. *Water Environment Research*, *79*(4), 396-405. https://doi.org/10.2175/106143006X111844

De Mes, T. Z. D., Stams, A. J. M., Reith, J. H., & Zeeman, G. (2003). *Status and perspectives of biological methane and hydrogen production*. In J. H. Reith, R. H. Wijffels, & H. Barten (Eds.). Dutch Biological Hydrogen Foundation. https: //www. ircwash. org/ sites/ default/files/Reith-2003-Bio.pdf#page=59

De Nardi, I. R., Del Nery, V., Amorim, A. K. B., Dos Santos, N. G., & Chimenes, F. (2011). Performances of SBR, chemical–DAF and UV disinfection for poultry slaughterhouse wastewater reclamation. *Desalination*, *269*(1), 184-189. https: //doi. org/ https: //doi. org/10.1016/j.desal.2010.10.060

Emmanuel, T. O., Bawo, K., & Lawrence, I. E. (2016). Evaluation of bacterial profile and biodegradation potential of abattoir wastewater. *African Journal of Environmental Science and Technology*, *10*(2), 50-57. https://doi.org/10.5897/AJEST2015.1945

García, J., Rousseau, D. P. L., Morató, J., Lesage, E., Matamoros, V., & Bayona, J. M. (2010). Contaminant Removal Processes in Subsurface-Flow Constructed Wetlands: A Review. *Journal of Critical Reviews in Environmental Science and Technology*, *40*(7), 561–661. https://doi.org/https://doi.org/10.1080/10643380802471076

Gomec, Y. C. (2010). High-rate anaerobic treatment of domestic wastewater at ambient operating temperatures: A review on benefits and drawbacks. *Journal of*

Environmental Science and Health, Part A, 45(10), 1169-1184. https:// doi. org/ https:/ doi.org/10.1080/10934529.2010.493774

Hendriks, A. T. W. M., & Zeeman, G. (2009). Pretreatments to enhance the digestibility of lignocellulosic biomass. *Bioresource Technology*, *100*(1), 10-18. https:// doi. org/ 10. 1016/j. biortech.2008.05.027

Irshad, A., Talukder, S., & Selvakumar, K. (2015). Current practices and emerging trends in abattoir effluent treatment in India: A review. *International Journal of Livestock Research, 5*(2), 13-31. https://doi.org/10.5455/ijlr.20150225043513

Jain, S., Jain, S., Wolf, I. T., Lee, J., & Tong, Y. W. (2015). A comprehensive review on operating parameters and different pretreatment methodologies for anaerobic digestion of municipal solid waste. *Renewable and Sustainable Energy Reviews, 52*, 142-154. https://doi.org/https://doi.org/10.1016/j.rser.2015.07.091

Jeong, H., Park, J., & Kim, H. (2013). Determination of NH_4^+ in Environmental Water with Interfering Substances Using the Modified Nessler Method. *Journal of Chemistry*, *2013*, 1-9. https://doi.org/http://dx.doi.org/10.1155/2013/359217

Jung, K. W., Lee, S. Y., Choi, J. W., & Lee, Y. J. (2019). A facile one-pot hydrothermal synthesis of hydroxyapatite/biochar nanocomposites: Adsorption behavior and mechanisms for the removal of copper(II) from aqueous media [Article]. *Chemical Engineering Journal*, *369*, 529-541. https://doi.org/10.1016/j.cej.2019.03.102

Kakaç, S., & Pramuanjaroenkij, A. (2016). Single-phase and two-phase treatments of convective heat transfer enhancement with nanofluids: A state-of-the-art review. *International Journal of Thermal Sciences*, *100*, 75-97. https:// doi. org/ https:// doi.org/ 10.1016/j.ijthermalsci.2015.09.021

Kato, M. T., Field, J. A., & Lettinga, G. (1997). Anaerobe tolerance to oxygen and the potentials of anaerobic and aerobic cocultures for wastewater treatment. *Brazilian Journal of Chemical Engineering*, *14*(4). https://doi.org/doi.org/10.1590/S0104-66321997000400015

Khalid, A., Arshad, M., Anjum, M., Mahmood, T., & Dawson, L. (2011). The anaerobic digestion of solid organic waste. *Waste Management*, *31*(8), 1737-1744. https:// doi. org/ 10.1016/j.wasman.2011.03.021

Körner, S., Das, S. K., Veenstra, S., & Vermaat, J. E. (2001). The effect of pH variation at the ammonium/ammonia equilibrium in wastewater and its toxicity to Lemna gibba. *Aquatic Botany*, *71*(1), 71-78.

Latif, U., & Dickert, F. L. (2014). *Biochemical Oxygen Demand (BOD)* (Vol. 2). Springer https://doi.org/https:/doi.org/10.1007/978-1-4939-1301-5_2

Lee, E., Bittencourt, P., Casimir, L., Jimenez, E., Wang, M., Zhang, Q., & Ergas, S. J. (2019). Biogas production from high solids anaerobic co-digestion of food waste, yard waste and waste activated sludge. *Waste Management*, *95*, 432-439. https:// doi. org/ 10. 1016/j. wasman.2019.06.033

Lemmer, A., Naegele, H. J., & Sondermann, J. (2013). How Efficient are Agitators in Biogas Digesters? Determination of the Efficiency of Submersible Motor Mixers and Incline Agitators by Measuring Nutrient Distribution in Full-Scale Agricultural Biogas Digesters. *Energies*, *6*, 6255-6273. https://doi.org/https:/doi.org/10.3390/en6126255

Li, J. (2010). *Nutrient Removal from Slaughterhouse Wastewater and Oxygen-Limited Partial Nitrification Process in Sequencing Batch Reactors* [Thesis, National University of Ireland]. Galway. http://www.nuigalway.ie/media/gene/files/JP-Li-thesis.pdf

Madsen, M., Holm-Nielsen, J. B., & Esbensen, K. H. (2011). Monitoring of anaerobic digestion processes: A review perspective. *Renewable and Sustainable Energy Reviews*, *15*(6), 3141-3155. https://doi.org/10.1016/j.rser.2011.04.026

Manjunath, N. T., Mehrotra, I., & Mathur, R. P. (2000). Treatment of wastewater from slaughterhouse by DAF-UASB system. *Water Research*, *34*(6), 1930-1936. https:// doi. org/ https://doi.org/10.1016/S0043-1354(99)00337-1

Martinez, F. A. C., Balciunas, E. M., Salgado, J. M., González, J. M. D., Converti, A., & De Souza Oliveira, R. P. (2013). Lactic acid properties, applications and production. A review. *Trends in Food Science Technology*, *30*(1), 70-83. https:// doi. org/ 10. 1016/j. tifs.2012.11.007

McCollom, T. M., & Seewald, J. S. (2001). A reassessment of the potential for reduction of dissolved CO_2 to hydrocarbons during serpentinization of olivine. *Geochimica et*

Cosmochimica Acta, *65*(21), 3769-3778. https:// doi. org/ 10. 1016/ S0016-7037(01)00655-X

Melo, R., Cabo, V. S., Branco, J., & Botelho, M. L. (2008). Gamma radiation induced effects on slaughterhouse wastewater treatment. *Radiation Physics and Chemistry*, *77*(1), 98-100. https://doi.org/https://doi.org/10.1016/j.radphyschem.2007.03.006

Menardo, S., Balsari, P., Tabacco, E., & Borreani, G. (2015). Effect of Conservation Time and the Addition of Lactic Acid Bacteria on the Biogas and Methane Production of Corn Stalk Silage. *BioEnergy Research*, *8*(4), 1810-1823. https: //doi. org/ https: /doi. org/10.1007/s12155-015-9637-7

Mittal, G. S. (2006). Treatment of wastewater from abattoirs before land application: A review. *Bioresource Technology*, *97*(9), 1119-1135. https: //doi. org/ https: //doi. org/ 10.1016/j.biortech.2004.11.021

Mittal, G. S. (2004). Characterization of the Effluent Wastewater from Abattoirs for Land Application. *Food Reviews International*, *20*(3), 229-256. https: //doi. org/ 10. 1081/ FRI- 200029422

Mutegoa, E., Kandola, I., Hilonga, A., & Njau, K. N. (2020). Evaluating the level of ammonia and sulfide in the liquid phase during anaerobic digestion of slaughterhouse waste operating at mesophilic scale digester: The impact of inhibition and process performance. *Energy*, *8*(4), 615.

Naik, S. N., Goud, V. V., Rout, P. K., & Dalai, A. K. (2010). Production of first and second generation biofuels: A comprehensive review. *Renewable and Sustainable Energy Reviews*, *14*(2), 578-597. https://doi.org/10.1016/j.rser.2009.10.003

Odong, R., Kansiime, F., Omara, J., & Kyambadde, J. (2013). The potential of four tropical wetland plants for the treatment of abattoir effluent. *International Journal of Environmental Technology and Management*, *16*(3), 203-222. https: //doi. org/ 10. 1504/IJETM. 2013.053640

Oliveira, S. C., & Sperling, M. V. (2009). Performance evaluation of UASB reactor systems with and without post-treatment. *Water Science and Technology*, *59*(7), 1299-1306. https:// doi.org/10.2166/wst.2009.138

Oller, I., Malato, S., & Sánchez-Pérez, J. A. (2011). Combination of Advanced Oxidation Processes and biological treatments for wastewater decontamination: A review. *Science of the Total Environment*, *409*(20), 4141-4166. https: // doi. org/ 10. 1016/j. scitotenv. 2010.08.061

Paschal, C., Gastory, L., Katima, J. H. Y., & Njau, K. N. (2017). Application of up-flow anaerobic sludge blanket reactor integrated with constructed wetland for treatment of banana winery effluent. *Water Practice & Technology*, *12*(3), 667-674. https: //doi. org/https:/doi.org/10.2166/wpt.2017.062

Philippe, F. X., Cabaraux, J. F., & Nicks, B. (2011). Ammonia emissions from pig houses: Influencing factors and mitigation techniques. *Agriculture, Ecosystems & Environment*, *141*(3), 245-260. https: //doi. org/ https: //doi. org/ 10.1016/ j.agee. 2011.03.012

Pierson, J. A., & Pavlostathis, S. G. (2001). Real-Time Monitoring and Control of Sequencing Batch Reactors for Secondary Treatment of a Poultry Processing Wastewater. *Water Environment Research*, *72*, 1-8. https: //doi. org/ 10.2175/ 106143000X138166

Prabhudessai, V., & Mutnuri, S. (2013). *Anaerobic Digestion of Food Waste in a Horizontal Plug Flow Reactor* [Thesis, Birla Institute of Technology And Science Pilani (Rajasthan) India]. http: //citeseerx. ist.psu. edu/ viewdoc/ download? doi=10.1.1.976.370 &rep=rep1&type=pdf

Reis, A. D. S., Savia, G., & Santos, S. M. (2016). Anaerobic treatment of food waste in pilot scale. *Water Practice & Technology*, *11*(4), 774-783. https: //doi. org/ .2166/ wpt.2016.084

Sakar, S., Yetilmezsoy, K., & Kocak, E. (2009). Anaerobic digestion technology in poultry and livestock waste treatment: A literature review. *Waste Management & Research*, *27*(1), 3-18.

Scano, E. A., Asquer, C., Pistis, A., Ortu, L., Demontis, V., & Cocco, D. (2014). Biogas from anaerobic digestion of fruit and vegetable wastes: Experimental results on pilot-scale and preliminary performance evaluation of a full-scale power plant. *Energy*

Conversion and Management, *77*, 22-30. https:// doi. org/ 10.1016/j. enconman. 2013.09.004

Shah, F. A., Mahmood, Q., Shah, M. M., Pervez, A., & Asad, S. A. (2017). Retracted: Microbial Ecology of Anaerobic Digesters: The Key Players of Anaerobiosis. *The Scientific World Journal*, *2017*, 21. https: //doi. org/ https: /doi. org/ 10. 1155/ 2017/ 3852369

Chen. S, Zhang. J, & Wang. X. (2015). Effects of alkalinity sources on the stability of anaerobic digestion from food waste. *Waste Management & Research*, *33*(11), 1033-1040. doi:10.1177/0734242X15602965

Sommer, S. G., Zhang, G. Q., Bannink, A., Chadwick, D., Misselbrook, T., Harrison, R., Hutchings, N. J., Menzi, H., Monteny, G. J., Ni, J. Q., Oenema, O., & Webb, J. (2006). Algorithms Determining Ammonia Emission from Buildings Housing Cattle and Pigs and from Manure Stores. *Advances in Agronomy*, 89, 261-335. Academic Press. https://doi.org/https://doi.org/10.1016/S0065-2113(05)89006-6

Sunder, G. C., & Satyanarayan, S. (2013). Efficient Treatment of Slaughter House Wastewater by Anaerobic Hybrid Reactor Packed with Special Floating Media. *International Journal of Chemical and Physical Sciences*, *2*, 2319-6602. https:// doi. org/ 10. 3390/ en6126255

Sunirat, R. (2016). *Enrichment and identification of ammonia tolerant microorganisms in different anaerobic waste treatment systems*. Rutgers, The State University of New Jersey]. https://rucore.libraries.rutgers.edu/rutgers-lib/49321/

Tsegaye, G., Asefa, B., & Kiros, S. (2018). Optimization of Biogas Production from Slaughterhouse Wastes. *African Journal of Environmental Science and Technology*, *12*(8), 283-295. https://doi.org/https:/doi.org/10.5897/AJEST2017.2456

Uddin, W., Khan, B., Shaukat, N., Majid, M., Mujtaba, G., Mehmood, A., Ali, S. M., Younas, U., Anwar, M., & Almeshal, A. M. (2016). Biogas potential for electric power generation in Pakistan: A survey. *Renewable and Sustainable Energy Reviews*, *54*, 25-33. https://doi.org/https://doi.org/10.1016/j.rser.2015.09.083

Vidal, J., Carvajal, A., Huiliñir, C., & Salazar, R. (2019). Slaughterhouse wastewater treatment by a combined anaerobic digestion/solar photoelectro-Fenton process performed in semicontinuous operation. *Chemical Engineering Journal*, *378*, 122097. https:// doi. org/ https://doi.org/10.1016/j.cej.2019.122097

Vymazal, J. (2010). Constructed Wetlands for Wastewater Treatment. *Water*, *2*, (3) 530-549. https://doi.org/https:/doi.org/10.3390/w2030530

Wang, K., Yin, J., Shen, D., & Li, N. (2014). Anaerobic digestion of food waste for volatile fatty acids (VFAs) production with different types of inoculum: Effect of pH. *Bioresource Technology*, *161*, 395-401. https: //doi. org/ 10.1016/ j.biortech. 2014.03.088

Wu, P. F., & Mittal, G. S. (2012). Characterization of provincially inspected slaughterhouse wastewater in Ontario, Canada. *Canadian Biosystems Engineering*, *54*, 6.9-6.18. https://www.researchgate.net/publication/269830851

Yaakob, M. A., Mohamed, R. M. S. R., Al-Gheethi, A. A. S., & Kassim, A. H. M. (2018). Characteristics of chicken slaughterhouse wastewater. *Chemical Engineering Transactions*, *63*, 637-642. https://doi.org/DOI:10.3303/CET1863107

RESEARCH OUTPUTS

(1) Research Article
(2) Poster Presentation