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

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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 is integrated with various units-biodigester, 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. 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%, respectively. In the present study, the unit-by-unit performance values achieved as a result of alterations to the facility's running conditions are presented. The MCS wastewater treatment facility was 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 Bureau of Standards (TBS).

Key words: biogas production, constructed wetland, effluent quality, meat industry pollution, slaughterhouse wastewater, wastewater treatment

Highlights

- A study of a novel slaughterhouse wastewater treatment system.
- Enough biogas produced onsite with energy-conversion potential.
- An efficient and energy-positive wastewater treatment system.
- Agitation time has influence on the amount of biogas produced.

Graphical Abstract

INTRODUCTION

Background information

Meat industry generates huge volumes of wastewaters that come from cleaning of slaughterhouse facilities, meat processing, and cleaning of animal carcasses (Bustillo-Lecompte & Mehrab 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 protein requirements of growing human populations (Emmanuel *et al.* 2016). Slaughterhouse wastewater contains biodegradable suspensions, colloidal particles, organic matter, fats, and cellulose that usually contribute to elevated levels of chemical oxygen demand (COD) and biochemical 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 it is discharged into the receiving aquatic environments (Irshad *et al.* 2015).

The present study dealt with wastewater treatment processes at the newly installed Mwanza City Slaughterhouse (MCS) wastewater treatment facility in Tanzania. Before the MCS wastewater treatment facility was installed, the effluents used to be released untreated to the nearby receiving waters that empty into Lake Victoria. The Mwanza City Council (MCC) strove to find funds to resolve pollution problems related to industrial effluents that fed into Lake Victoria. The World Bank (WB) funded the construction of the slaughterhouse wastewater treatment facility through the Lake Victoria Environmental Management Project (LVEMP).

The LVEMP then contracted the Nelson Mandela African Institution of Science and Technology (NM-AIST) to design and supervise 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), total suspended solids (TSS) (9,700 mg/L), BOD_5 (1,200 mg/L), COD (4,500 mg/L), NH_3-N (65 mg/L), SO_4^{2-} (370 mg/L), and faecal coliforms (2×10^7 CFU/100 mL). The mean initial two-month performance after construction of the MCS wastewater treatment facility revealed that effluent contaminant levels were above the TBS regulation (Table 1).

Facility design considerations

The MCS wastewater treatment facility was designed with several units such as pretreatment unit (screening, oil and fat/grease trap and buffer tank), biodigester unit (stirred batch upflow anaerobic

Table 1 | Initial performance levels of the MCS wastewater treatment facility in comparison to the maximum allowed TBS guidelines

Measured parameter	In	Out	Allowed TBS limits	Overall efficiency (%)
BOD_5 (mg/L)	1,013 ± 128	127 ± 19	30	87.5
COD (mg/L)	4,606 ± 582	359 ± 28	60	92.2
TSS (mg/L)	9,592 ± 105	134 ± 14	100	98.6
NH_4^+	73.8 ± 2.1	42.1 ± 1.3	10	43
Fecal coliforms (counts/100 mL)	32,000 ± 869	750 ± 32	1,000	97.7
NO_3^- (mg/L)	338 ± 18	117 ± 12	50	65.4
NH_3 (mg/L)	582 ± 34	89 ± 8	N.I.[a]	84.7
Turbidity (NTU)	9,859 ± 128	393 ± 39	300	96

[a] N.I., Not indicated in the standards.

sludge blanket (UASB)), advanced treatment (aeration tank and clarifier) and a polishing step (constructed wetland). Also, the facility has subcomponents such as a biogas holder and a sludge drying bed. This makes it one of the novel systems that has, so far, not been extensively studied. During the study, the MCS wastewater treatment facility was energy positive because the daily energy consumption ranged between 50 and 65 kWh while 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 aim of the present study was to investigate the performance of the MCS wastewater treatment facility by taking into account the factors that affect operational efficiencies.

MATERIALS AND METHODS

Study area

The MCS wastewater treatment facility is located along Musoma Road, Mahina Ward in Mwanza, Tanzania (Figure 1). 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 on the southern shores of Lake Victoria and has a population of approximately four million according to the national census of 2012.

Treatment system design

The system was designed to have the following parameters: feed flow rate, $Q = 65\ m^3/h$; the dimensions of the batch stirred biodigester were: diameter of 10 m, total height of 8.50 m with water

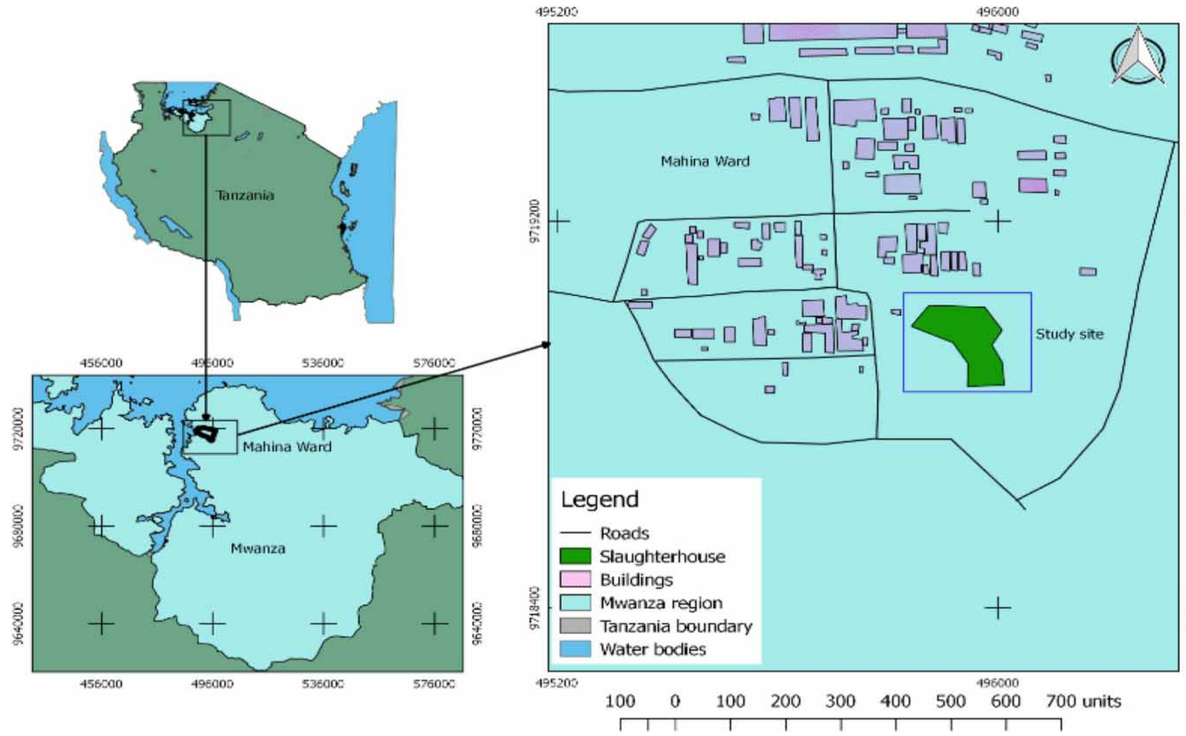

Figure 1 | Map of Tanzania (top left corner) showing the location of Mwanza city (lower left) and a zoom-in of the MCS wastewater treatment facility.

level height of 6.62 m, a gas collector height of 1.38 m and a free body space of 0.50 m. The biodigester was designed to degrade 4,500 mg/L of influent COD, BOD_5 of 1,200 mg/L, TSS of 9,700 mg/L and NO_3^- of 605 mg/L. The designed hydraulic detention time, τ, was 4 days. The aeration tank has of diameter of 7 m, and 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.

Wastewater treatment at the MCS

The MCS wastewater treatment facility was operated as a semi-batch system, providing an intermittent flow of wastewater into the different units of the plant up to the constructed wetland (Figure 2). The facility was designed to match its operation hours taking into account the fact that slaughter activities normally happen between 3 and 6 AM. The generated wastewater was quickly transferred into the biodigester to minimize biomethanation. Pumping into the biodigester was usually done for 1–2 h. The biodigester was fed from the bottom up. From the biodigester, the wastewater was transferred by gravity to be further treated in the aerated tank. Aeration was done for 12 h, then stopped to allow development of anoxic conditions for another 12 h. This mode of operation assisted 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.

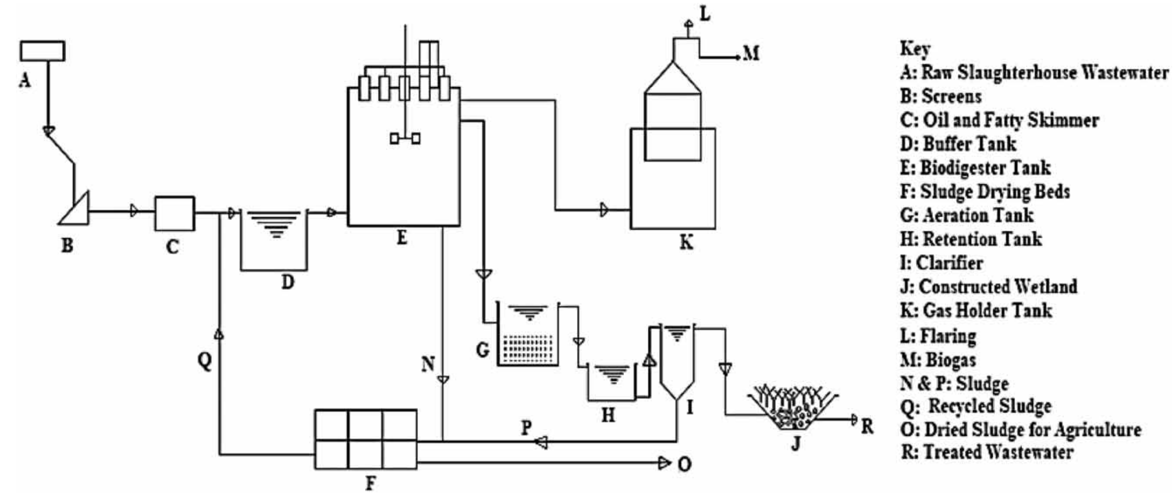

Figure 2 | The scheme of the operated MCS wastewater treatment facility.

After the aeration unit, there was a retention tank and a pump that continuously fed 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 the small number of animals slaughtered per day. Animals slaughtered at the MCS facility included goats, cattle, and sheep. In the course of the present study, the wastewater samples collected were found to contain high amounts of large solids from undigested offal. The solids were removed from the system using coarse and fine bar screens of 20 mm and 7.5 mm spacing, respectively, 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 from the wastewater before the water entered the polishing step. The sludge that accumulated in the clarifier was transferred into the sludge drying beds; later it was 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, width of 3.75 m (which made a total length of 16.5 m and width of 3.75 m), and height of 1.2 m. Inlet diameter channel was 100 mm, terminating at 300 mm above the sand surface.

Effluents from the clarifier 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 the wastewater. The constructed wetland was divided into two cells each with dimensions of 30 m length, 10 m width and 1 m depth. The wetland effective treatment depth was 0.5 m and granite gravel packing was of 20 mm size with porosity of 0.4. The daily influent to each of the constructed wetland cells was around 16 m^3. During the course of the present study, the constructed wetland was observed to have a retention time of around 3.3 days.

Onsite measurements

Onsite measurements for EC, pH, TDS, temperature, and DO were 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).

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, an analysis of influent and effluent wastewater was carried out. Wastewater sampling and analysis were done for five consecutive months. A performance evaluation period was started after two months of the trial runs, where the plant performance observed was as shown in Table 1. In this period, a total of 112 samples were taken and analyzed.

Duplicate wastewater samples from the 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 analyses were acidified using sulfuric acid to a pH below 2 to deactivate microbial activities while another sample was not acidified, as they could be transferred to reach the NM-AIST laboratory within 24 hours while packed in ice-packed cool boxes and kept at a temperature below 4 °C.

Laboratory analysis

The determination of NH_4^+, NO_3^- and NH_3 concentrations was done using a spectrophotometer (Hach DR-2800™). The analysis of NH_3 and NH_4^+ used the Nessler method as detailed by 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 environmental contamination indicators were analyzed as per the standard methods for examinations of water and wastewater (APHA 2012). The 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 1,100 °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.

RESULTS AND DISCUSSION

General operational conditions

The present study was carried out for a period of five months, in the months of February to June 2019. The daily amount of wastewater fed into the biodigester at the MCS averaged 32.7 m^3. This wastewater volume, produced through animal slaughter and related activities, was a fraction of the design value of 130 m^3 per day. The difference was attributable to the lower number of animals that was being slaughtered per day compared to the design capacity. The design capacity was for the facility to slaughter about 750 animals per day. During the course of 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 DO were measured onsite (Table 2). The present study observed that the MCS wastewater treatment facility was operating at a temperature of around 26.3 ± 0.3 °C. This ambient temperature was lower than that recommended in other studies; that is, a mesophilic temperature ranging from 30 to 40 °C for essential enhancement of treatment efficiency as well as biogas production (Tsegaye *et al.* 2018). Thus, treatment efficiency of the MCS bioreactor can be significantly improved by raising this temperature either 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, these improvements were not possible. However, this has remained to be a recommendation for further improvement.

Table 2 | Physico-chemical operational conditions for MCS 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	2.06 ± 0.2

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 6.5–8.0 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). 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, respectively. 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. The low DO in the aeration tank compared with the anticipated 5 mg/L 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.

DO in anaerobic digesters may be caused by factors such as high mixing rates, high recirculation rate, and too much loss of activated sludge (Kato *et al.* 1997; Botheju & Bakke 2011). Conklin *et al.* (2007) studied the influence of DO on anaerobic digestion processes and found that a supply of 3–4 mg/L of DO led to 27% of active methanogenesis. These researchers concluded that a short-term oxygen exposure did not significantly reduce methanogen activity. However, a continuous oxygen exposure was found to negatively affect the methanogenic biomass activity. In spite of 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 important to monitor DO loadings into the digester to improve the long-term methanogenic activity of the facility.

Effects of agitation on biogas production

The effects of agitation time on the biodigester was investigated for zero to 6 h of agitation. The effects caused by both biodigester agitation duration and influent wastewater volume on the amount of biogas produced at the MCS wastewater treatment facility have been indicated (Table 3). Each of the agitation times was run once per day for 7 days and the 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. 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). It has also been found by other researchers that a gentle biodigester agitation distributes uniformly the substrates 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 3 | The combined effect of agitation time and influent wastewater volume on biogas production at the MCS 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

Biodigester unit performance

The biodigester performance for the removal of important environmental pollutants has been indicated (Table 4). Transformation of N and N-compounds and related mass balance explanations are found in Equations (1)–(7) below.

Alkalinity within an acceptable level is known to favour biogas production through maintenance of pH (Prabhudessai & Mutnuri 2013; Jung *et al.* 2019). An acidic environment in the biodigester is inhibitive in terms of biogas production (Sakar *et al.* 2009; Lee *et al.* 2019). Thus, for optimal biogas production, maintenance of alkalinity as $CaCO_3$ within a favourable range is important. NH_4^+ 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 was decreasing while the VFAs was increasing 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 4), which indicates that the buffering system was overloaded by the increase of VFAs. However, the VFA-to-alkalinity ratio under the present study was still in the acceptable range as per Shujun *et al.* (2015), who indicated that for a well-working digester, the VFA-to-alkalinity ratio falls between 0.3 and 0.4.

$$NH_3 + H_2O + CO_2 \rightarrow NH_4(HCO_3) \tag{1}$$

In the present study, at pH value of 7.2, the NH_3 to NH_4^+ ratio was about 0.5 (Table 4). This was consistent with a recent study that investigated ammonia levels in 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 known to be 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 for this high ammonia concentration is unknown. However, a study by Jeong *et al.* (2013) pointed out the deficiency of titrimetric methods in estimating the concentration of ammonia species in wastewater, especially when 'hindering' ions such as Mg, Cl, and Fe are present in high concentrations. It is possible that ammonia was overestimated in the present study due to the fact that, during the study, 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.

A relatively high–that is, >60% removal efficiency – was achieved in the biodigester unit for BOD_5, COD, TSS, nitrate, and turbidity (Table 4). 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

Table 4 | Performance of the biodigester for removal of key environmental contaminants

Performance parameter	In	Out	Expected design efficiency (%)	Actual biodigester efficiency (%)
BOD_5 (mg/L)	960 ± 159	320 ± 27	71.7	66.7
COD (mg/L)	4,032 ± 624	1,312 ± 86	78	67.5
TSS (mg/L)	10,100 ± 428	2,860 ± 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 coliforms (CFU/100 mL)	37,667 ± 1,058	19,333 ± 482	45.2	48.7
Turbidity (NTU)	17,600 ± 373	4,020 ± 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

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 anoxic conditions in the biodigester, 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).

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

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

Under the anoxic conditions in the biodigester, NO_3^- is also removed through the denitrification process as suggested by Sheng *et al.* (2013). In nature, denitrification can take place in both terrestrial and aquatic ecosystems. Denitrification is usually facilitated by a broad variety of denitrifying bacteria, which degrade the organic material by using NO_3^- in the absence of oxygen as indicated in Equation 4 (Roy & Conrad 1999). The loss of NO_3^- can also be a result of a process in which NO_3^- is reduced to nitrogen gas (Equation 5). Typically, denitrification occurs in anoxic environments where the concentration of dissolved and freely available oxygen is depleted. In these areas, NO_3^- or NO_2^- can be used as a substitute terminal electron acceptor instead of oxygen, a more energetically favorable electron acceptor (Equation 5). The terminal electron acceptor is a compound that gets reduced in the reaction by receiving electrons. The complete process can be expressed as a net balanced redox reaction, where NO_3^- gets fully reduced to N_2 as discussed by Sheng *et al.* (2013).

$$24NO_3^- + 5C_6H_{12}O_6 \rightarrow 12N_2 + 30CO_2 + 18H_2O + 24OH^- \tag{4}$$

$$2NO_3^- + 10e^- + 12H^+ \rightarrow N_2 + 6H_2O \tag{5}$$

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. 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. Sources of NH_4^+ vary, including the hydrolysis of urea (Equation 6) and undigested protein degradation; the latter source is slow and of secondary importance. NH_4^+ is further transformed to nitrite and nitrate by autotrophic microorganisms as indicated in Equation (7). During the transformation of NH_4^+ into nitrite, a greenhouse gas (that is, N_2O) is usually formed as an intermediate (Sommer *et al.* 2006). The formation of nitrous oxide has thus raised great interest in the study of nitrification.

$$CO(NH_2)_2 + 3H_2O \rightarrow 2NH_4^+ + HCO_3^- + OH^- \tag{6}$$

$$NH_4^+N \xrightarrow{\text{Primary nitrifiers}} NO_2^- \xrightarrow{\text{Nitrobacter}} NO_3^- \tag{7}$$

Treatment processes in the biodigester were energy-positive, involving simple mechanisms shown in Equations (4)–(7). The expected design and actual performance of the biodigester were satisfactory (Table 4) 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 the one that was 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.

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^+ (48.2%), faecal coliform (46.6%), NO_3^- (58.3%), NH_3 (66.5%) and turbidity (66.9%) has been given (Table 5). The aeration system was run for 12 h a day. Compared to the performance of the biodigester (Table 4), the aeration tank consumed the influent NH_4^+ (Table 5). 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. In the aeration tank, treatment processes took place in a linear manner (Equations 8–11). Equations (8) and (9) show processes that occurred during the 12 h of aeration. In Equations (10) and (11), ammonia was acidified using microbes through denitrification processes in the other 12 h of the day with no aeration.

$$NH_4^+N \xrightarrow{\text{Assimilation}} NO_2^- \tag{8}$$

$$NO_2^- \xrightarrow{\text{Assimilation}} NO_3^- \tag{9}$$

$$NH_3 + 3/2O_2 \xrightarrow{\text{Nitrosomonas}} HNO_2 + H_2O + \text{Biomass} \tag{10}$$

$$HNO_2 + 1/2O_2 \xrightarrow{\text{Nitrobacter}} HNO_3 + \text{Biomass} \tag{11}$$

In comparison to design, removal efficiencies in the aeration step were satisfactory (Table 5). With the exception of COD, removal efficiencies for each contaminant were either better than the anticipated design values or within a 10% error. The COD removal had a 20% error.

Table 5 | Performance of the aeration tank (AT) for removing the key environmental contaminants

Measured parameter	In	Out	Expected design efficiency (%)	Actual AT efficiency (%)
BOD_5 (mg/L)	320 ± 27	155 ± 23	56.4	51.6
COD (mg/L)	1,312 ± 86	624 ± 81	66.1	52.4
TSS (mg/L)	2,860 ± 284	1,040 ± 154	60.5	63.6
NH_4^+ (mg/L)	550 ± 18	285 ± 6	29.4	48.2
Fecal coliform (CFU/100 mL)	19,333 ± 482	10,324 ± 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)	4,020 ± 144	1,934 ± 96	56.7	51.9

Constructed wetland performance

When 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* p*apyrus 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 complex, involving several bacterial groups, each with its own optimum working conditions. It is possible that microbes in the CW were sensitive to some process parameters including alkalinity, pH, VFAs, temperature, etc. Thus,

Table 6 | Performance of the constructed wetland (CW) in the removal of the environmental pollutants

Measured parameter	In	Out	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)	1,040 ± 154	40 ± 6	97.2	96.2
NH_4^+ (mg/L)	285 ± 6	5 ± 1	99.1	98.2
Fecal coliforms (CFU/100 mL)	10,324 ± 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)	105.5 ± 12.8	5.0 ± 1	97.6	95.3
Turbidity (NTU)	1,934 ± 96	12.5 ± 1.2	99.1	99.4

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 CW and 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 (12).

$$\text{Organic Carbon} + O_2 \xrightarrow{\text{Heterotrophs}} CO_2 + \text{Biomass} \tag{12}$$

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 actual performance of the constructed wetland 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 (Vymazal 2010; Paschal *et al.* 2017). 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 efficiencies >78% (Table 6).

Performance of the integrated system

The overall performance of the biodigester-constructed wetland system has been provided (Table 7). 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^+ (191.0%), faecal coliform (99.1%), NO_3^- (93.3%),

Table 7 | The five months' overall performance of the integrated biodigester-constructed wetland for removal of environmental pollutants

Measured parameter	In	Out	Allowed TBS limits	Expected efficiency (%)	Overall efficiency (%)
BOD_5 (mg/L)	960 ± 159	25 ± 3	30	98.2	97.4
COD (mg/L)	4,032 ± 624	68 ± 9	60	99.1	98.3
TSS (mg/L)	10,100 ± 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)	37,667 ± 958	330 ± 15	1,000	98.7	99.1
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.[a]	98.9	99.1
Turbidity (NTU)	17,600 ± 373	12.5 ± 1.2	300	99.2	99.9

N.I.[a] = Not indicated in the standards.

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 that were performing complementary treatment tasks. Previous research found that for soluble COD removal, good bioreactor operations 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 7).

Furthermore, the MCS wastewater treatment facility was designed to produce a sludge volume of about 19,400 and about 5,700 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 15,800 m^3 and 5,300 m^3 per year from the biodigester and aeration tanks, respectively. Sludge produced at the MCS facility is usually applied as fertilizer to boost plant production in nearby agricultural fields.

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).

Energy consumption

The electrical energy consumption for the 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 1,950 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 (Figure 3). 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.

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 8). Normally, 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 course of the present study.

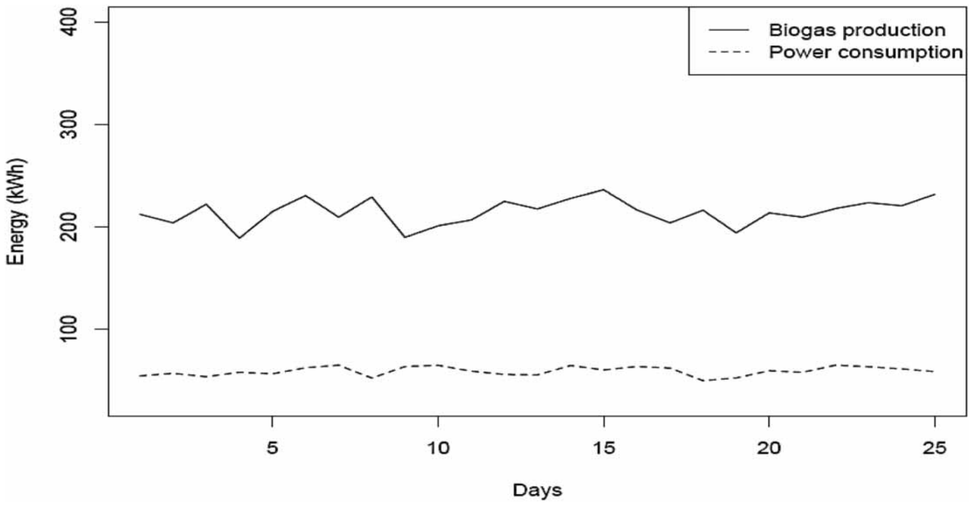

Figure 3 | Relationship between energy consumption and the MCS wastewater treatment facility's biogas production in 25 days of a month. Daily biogas volume produced was converted into electrical energy (kWh).

Table 8 | Composition of the biogas produced at the MCS wastewater treatment facility

Constituent	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

CONCLUSIONS

Slaughterhouse wastewater treatment is still a challenge not only to countries in sub-Saharan Africa but also in other developing countries across the world. To solve the energy issues at the study site, the present study is recommending that the MCC should invest in an energy conversion system to benefit from the biogas produced. The MCC should also consider the installation of 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 that 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 1–2 h per day was found to yield maximum biogas of about 185–231 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 nearby users at a relatively affordable cost.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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