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Modification of municipal wastewater for improved biogas recovery

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Abstract

The energy demand, which is expected to increase more worldwide, has sparked the interest of researchers to find sustainable and inexpensive sources of energy. This study aims to integrate an energy recovering step into municipal wastewater treatment plants (MWWTPS) through anaerobic digestion. The anaerobic digestion of municipal wastewater (MWW), and then co-digestion with sugar cane molasses (SCM) to improve its organic content, was conducted at 25 °C and 37 °C. The results showed a substrate mixture containing 6% of SCM and total solids (TS) of 7.52% yielded a higher amount of biogas (9.73 L/L of modified substrate). However, chemical oxygen demand (COD) of the resulting digestate was high (10.1 g/L) and pH was not stable, and hence needed careful adjustment using 2 M of NaOH solution. This study recommends a substrate mixture containing SCM (2%) and TS (4.34%) having biogas production (4.97 L/L of modified substrate) for energy recovery from MWWTPS, since it was found to have more stable pH and low COD residue (1.8 g/L), which will not hold back the MWW treatment process. The annual generation of modified substrate (662,973 m^3) is anticipated to generate about 16,241 m^3 of methane, which produces up to 1.8 GWh and 8,193 GJ per annum.

Key words: anaerobic digestion, biogas, municipal wastewater, sugarcane molasses

Highlights

- The co-digestion of sugarcane molasses (SCM) and municipal wastewater (MWW) for integrating an energy recovery system in the municipal wastewater treatment process was studied.
- At a total solids (TS) of 7.52%, biogas recovery was increased from 1.46 to 9.73 L/L of substrate.
- Use of modifiers of high CN ratio results in small volumes of modifiers needed to increase biogas yield.
- The use of a CHP engine for the conversion of biogas to heat and electrical energy increases the energy value of the wastewater and can be an incentive for wastewater treatment companies.
- The integration of the biodigester into the available oxidation ponds allows adequate treatment to meet discharge limits.

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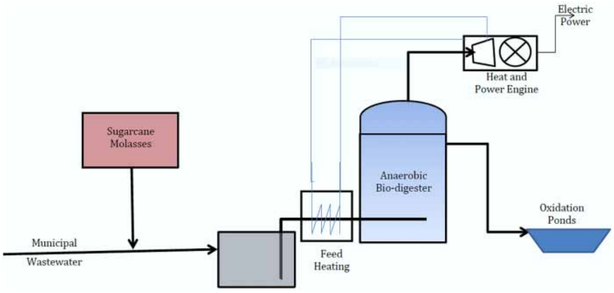
Graphical Abstract



INTRODUCTION

The use of fossil fuels to meet the increasing energy demand has led to several environmental problems like acidic rains, global warming and air pollution in both developed and developing countries. These negative effects can greatly be reduced by using renewable sources of energy (Karekezi 2002). While fossil fuels are depleting rapidly, the demand for energy is expected to increase by more than 50% by 2025 worldwide (Cheerawit *et al.* 2012). This has subsequently led to increased research in attempts to develop sustainable, inexpensive and environmentally-friendly energy from renewable sources to reduce the consumption of fossil fuels (Ellabban *et al.* 2014). Anaerobic digestion of both solid and liquid wastes to recover biogas is considered as one of the most important renewable energy sources and offers the double benefit of treating wastes while producing energy at the same time (Ellabban *et al.* 2014).

The global production of municipal wastewater (MWW) was estimated to be 900 million m^3 per day in 2015 and projections were that it would grow every year proportional to population growth (Mateo-Sagasta *et al.* 2015). In Tanzania, waste stabilization ponds (WSPs) receive about 407,488 m^3 of MWW daily (Kihila *et al.* 2015). MWW can be enhanced via innovative modifications and upgrading the treatment technique to achieve energy positive operation through anaerobic digestion for biogas recovery (Wett *et al.* 2007). Literature shows that MWW with a typical organic matter content of 1,500–2,000 mg COD/L contains potential chemical energy for recovery (Tchobanoglous *et al.* 2003). However, MWW is a much diluted mixture, hence low emission of methane, higher methane solubility and unbalanced carbon to nitrogen (C/N) ratios (Guven *et al.* 2019b). In order to achieve the energy recovery process, organic matter content is concentrated by conventional bio flocculation methods, though they suffer from low removal efficiency, high energy consumption and are definitely expensive for developing countries, and hence less applied (Lin *et al.* 2017). As such, there is a need to investigate ways to overcome these limitations by co-digesting MWW with materials containing high organic matter contents like sugarcane molasses (SCM) for higher biogas yields.

SCM is the main byproduct of sugar-refining industries and contains a high amount of sugars and nutrient minerals. It is commonly used as raw material for alcohol production and livestock feeds (Park *et al.* 2010). The SCM contains a large amount of organic matter due to its large amount of sugars and high C/N ratios (Iqbal *et al.* 2014). Due to this fact, it can be used to adjust the C/N ratio of carbon-poor substrates such as MWW to maintain the equilibrium capacity of the bioreactors and enhance biodegradation for optimal production of biogas. A number of reports exist on co-digestion processes, such as co-digestion of the organic fraction of municipal solid waste, agricultural organic wastes, sewage sludge (Ponsá *et al.* 2011) and more specific wastes. Nevertheless, few studies introduced the stream of organic matter into MWW for energy recovery (Guven *et al.* 2019a). Other

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studies have used SCM as a single substrate to enhance biogas production (Iqbal *et al.* 2014) or in co-digestion (Lee *et al.* 2014).

To the best of our knowledge, no report exists on anaerobic co-digestion of MWW and SCM as the mechanism of improving energy recovery and enhancing MWW treatment. Therefore, in the present study, the digestion of MWW and co-digestion of six different MWW/SCM ratios, under mesophilic conditions using cow dung sludge as inoculum, were evaluated in terms of biogas yield, methane content, COD removal and stability of the process. The estimation of the potential heat and electricity production to reinforce the purpose of integrating the energy recovering step in wastewater treatment system was done.

MATERIAL AND METHODS

Characteristics of Moshi municipal wastewater

The Moshi municipality wastewater treatment system is operated by the Moshi Urban Water and Sewerage Authority (MUWSA). The system uses WSPs to treat 4,500 m^3 of the MWW per day. The supply of wastewater to the treatment plant is by a central sewer which covers about 46% of the urban population. The daily average inflow to the WSPs is 4,221.2 m^3/d and the outflow is estimated at 2,452.6 m^3/d (Kihila *et al.* 2015). Annual average characteristics of the raw wastewater entering the anaerobic pond are shown in Table 1.

Table 1 | Characteristics of the raw wastewater entering the anaerobic pond

Parameter	Annual mean ± standard deviation
Flow in (m^3/day)	4,221.2 ± 119.6
COD (mg/L)	1,559.1 ± 86.5
Sulphide (mg/L)	0.7 ± 0.5
Ammonia (mg/L)	79 ± 21.4
Nitrate-Nitrogen (mg/L)	49.9 ± 19.7
Nitrate (mg/L)	143.4 ± 12.7
pH	7.6 ± 0.4
Temperature (°C)	25.4 ± 0.9
Conductivity (μS/cm)	697.2 ± 116.8
TDS (mg/L)	926.1 ± 53.9
BOD_5 (mg/L)	840.6 ± 49.1

Source: Moshi Urban Water and Sewerage Authority (MUWSA) (2018).

Co-substrates and inoculum

The MWW used in this study was obtained from the inlet of the anaerobic pond of the Moshi MWWP in Kilimanjaro, Tanzania. SCM was collected from Tanganyika Planting Company Limited (TPC) in Moshi, Tanzania, which produces an excess of 13,000 tons of SCM per year and is situated 21 km south-west of the municipal wastewater treatment plant. The inoculum was obtained from an anaerobic digester treating cattle manure as its feedstock at Kikwe village in Arusha, Tanzania. The substrates and the inoculum were individually homogenized and stored in a refrigerator (4 °C) while waiting for use (Wang *et al.* 2012). The characteristics of substrates and inoculum are shown in Table 2.

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Table 2 | Characteristics of the substrate, modifier and inoculum used for the co-digestion

Characteristics	Moshi MWW	Modifier (SCM)	Inoculum
pH	6.15	5.8	7.34
Total solids (TS) (%)	2.76	82.2	28.31
Total volatile solids (TVS) (%)	78.85	86.71	67.28
Total moisture (%)	97.24	17.8	71.69
Ash (%)	21.15	13.29	32.72
Total carbon (%)	36.53	37.62	38.47
Total nitrogen (%)	3.44	0.58	1.61
C/N ratio	10.6:1	64.8:1	23.8:1
COD (g/L)	2.2	620	N.D
BOD (g/L)	1.2	N.D	N.D

N.D, Not determined.

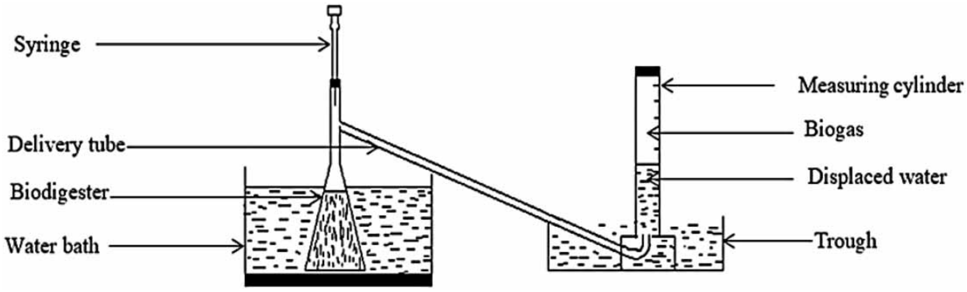

Figure 1 | Laboratory set up for the anaerobic digestion of municipal wastewater and modified substrates.

Batch experimental procedures

The experiments were done in anaerobic batch reactors (Figure 1) with a working volume of 1 L operated at temperature (25 °C ±1) and mesophilic temperature (37 °C ±1) in the laboratory of the Nelson Mandela African Institution of Science and Technology in Arusha, Tanzania. In order to initiate the anaerobic digestion of the co-substrate, 10% (*v/v*) of inoculum was added to the anaerobic digesters, and named batch experiment 1, 2, 3, 4, 5 and 6. About 1 L of the modified substrate (MWW and SCM mixture) was prepared with mixing ratios (v/v %) of 100:00, 98:02, 96:04, 94:06, 92:08 and 90:10 to make C/N ratios of 10.6, 15.7, 20, 23.8, 27.1 and 30.4 respectively. About 90% (v/v) of each modified substrate was added into the digesters containing the inoculum and the pH of the co-substrate was adjusted and maintained between 6.5 and 7.5 using 2 M of NaOH solution for the stability of anaerobic digestion. The biodigesters were then made airtight using rubber stoppers after flushing with nitrogen gas for 10 min to maintain the anaerobic environment inside the digestate bottles. An outlet from the biodigester was connected with a 10 mm cylindrical tube for collecting biogas in a measuring cylinder with a volume of 1,000 mL by the displacement method. The daily biogas production was obtained through the measurement of the displaced water. The quantity of biogas from each digester was recorded daily and the methane composition after every 3 days. The biodigesters were gently shaken to mix the floating layer regularly once a day. Biogas production was monitored periodically until gas production became negligible.

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Analytical methods

During the anaerobic digestion experiments, the following were analyzed: the chemical oxygen demand (COD), biological oxygen demand (BOD), total nitrogen (TN), total carbon (TC), total solid (TS), volatile solids (VS), total moisture (TM), total volatile fatty acid as acetic acid (VFA), total alkalinity as calcium carbonate (alkalinity), pH and temperature. The COD concentration was determined by the close-refluxing method using a spectrophotometer (DR2800). The BOD_5 measurement was performed by the respirometric method for five days using an OxiTop TS 606/2-i system. The TC and TN were quantified using the Thermo Scientific FLASH 2000 HT Elemental analyzer. C/N ratios of the modified substrates were determined by using the Cornell compositing method (Chen *et al.* 2011). The TS and TM were determined gravimetrically by drying the homogenized samples at 105 °C for 24 hours. The VS fraction was also gravimetrically determined by incinerating in a muffle furnace at 550 °C for 1 hour. The calculations for solids determination were done according to Sluiter *et al.* (2008). The VFA and alkalinity were determined by simple titration. The pH and temperature was measured using a pH meter (Beckman pH 211). Before using the instruments, they were first calibrated using standard solutions as per *Standard Methods for the Examination of Water and Wastewater* (APHA 2012). The biogas content analysis was done by using a biogas analyzer (DR 5000).

Statistical data analysis was done using Origin Pro 8 to analyze the biogas production potential from different batch experiments and their correlation.

Biogas yield

The biogas yield of each mixed ratio (L/g COD) was calculated as the ratio between the cumulative volume of biogas to the amount of COD added to the biodigester times the volume of the substrate mixture used, as shown in Equation (1).

$$Y = \frac{V_{g-Total}}{(COD_i)x\ V_s} \tag{1}$$

where

Y = biogas yield (mL/gCOD)
$V_{g-Total}$ = cumulative volume of biogas (mL)
COD_i = initial COD of substrate (g/L)
V_s = volume of substrate used (L)

Additionally, the COD removal efficiency (%) was calculated as a percentage of the ratio between the COD removed by the digester and the COD added to the digester, as shown in Equation (2).

$$COD\ removal\ (\%) = \left(\frac{COD_i - COD_f}{COD_i}\right) \times 100 \tag{2}$$

where

COD_i = Initial COD (g/L)
COD_f = Final COD (g/L)

Heat and power estimation

The amount of biogas produced per m^3 of the substrate mixture was estimated from the mixing ratio with lowest amount of modifier and low final COD. The biogas was estimated by comparing the

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amount of biogas obtained from the experiment to the amount of substrate that could be formed from Moshi MWWTP per year. Then the biogas produced was used to determine its heat and electrical energy potential. The gas turbine, which uses combined power and heat engine (CHP) to convert biogas into heat and electricity with an efficiency of electricity 35–40% and heat 45–50%, was used as the conversion technology for the estimation of the energy produced (Jørgensen 2009). The estimation was done by considering the smallest efficiency in both heat and electricity as shown in Equations (3) and (4) respectively. The amount of heat produced from 1 m^3 of pure methane (100%) is 39.8 MJ, which is equivalent to 11.06 kWh (Jørgensen 2009).

$$TH_{biogas} = C_{CH4} \times CV_{CH4} \times TV_{biogas} \times \epsilon \tag{3}$$

where

TH_{biogas} = Estimated total heat produced by the total volume of biogas (MJ)
C_{CH4} = Average content of methane (%v/v)
CV_{CH4} = Calorific value of pure methane (MJ/m^3)
TV_{biogas} = Estimated total volume of biogas (m^3)
$\in$ = Conversion efficiency of CHP system (%)

$$TP_{biogas} = C_{CH4} \times TP_{CH4} \times TV_{biogas} \times \in \tag{4}$$

where

TP_{biogas} = Estimated total power produced by the total volume of biogas (KWh)
C_{CH4} = Average content of methane (%)
TP_{CH4} = Total power of pure methane (KWh/m^3)
TV_{biogas} = Estimated total volume of biogas (m^3)
$\in$ = Conversion efficiency of CHP system (%)

RESULTS AND DISCUSSION

Substrates characteristics for biogas production

The feedstock, modifier, and inoculum used in this study were analyzed for their physicochemical characteristics and the results are as shown in Table 2. The VS of MWW and SCM were 78.85% and 86.71% respectively, indicating the potential of these substrates for biogas production by anaerobic digestion since biogas and methane yield depends on the biodegradable transformation of VS (Buffiere *et al.* 2006). The moisture contents of these two substrates were 97.24% and 17.8% respectively, an indication that the MWW was very dilute for good biogas generation from anaerobic digestion (Cheerawit *et al.* 2012; Guven *et al.* 2019a) while the SCM was too concentrated for the same purpose (Iqbal *et al.* 2014).

The C/N ratio was 10.6 for MWW and 64.9 for SCM, both out of the range required to balance the main nutrient for the growth of anaerobic bacteria and the stability of the biodigester (Zhang *et al.* 2016). Available literature suggests that the appropriate C/N ratio for optimum conditions of anaerobic digestion ranges from 20 to 30 (Wang *et al.* 2012).

All substrates were slightly acidic; for the optimal production of biogas, pH must be around neutral (Hagos *et al.* 2017). It was therefore important to adjust and maintain the pH of the substrates in the range of 6.3–7.8 throughout the anaerobic digestion process. The volatile solids, pH and C/N ratio of the inoculum were all in the optimal range for the ideal biogas production. Cattle manure was considered as a good inoculum because it has a wide diversity of microorganisms and optimal C/N

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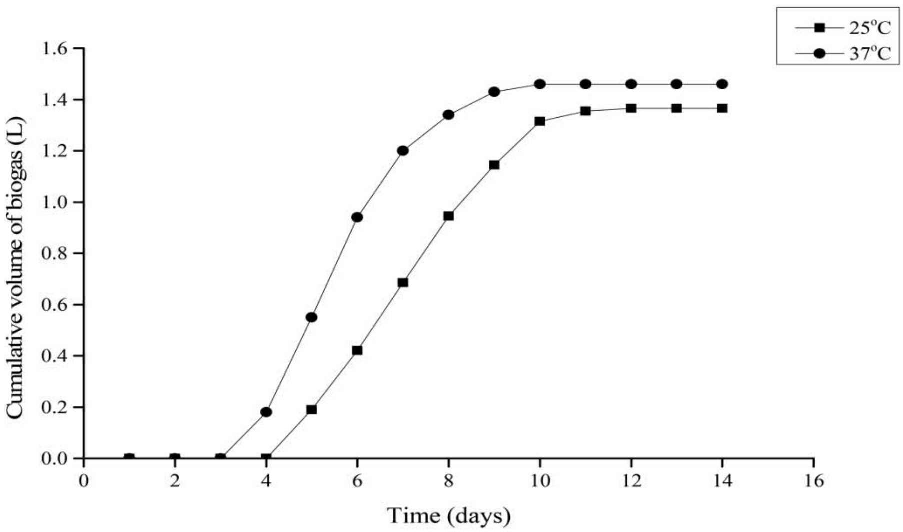

Figure 2 | Effect of temperature (°C) on the cumulative volume of biogas.

ratio, which ensures a sufficient level of hydrolytic and methanogenic activity in a wide range of substrates.

The effect of temperature on cumulative biogas yields from municipal wastewater

Figure 2 shows that, from the anaerobic digestion of the MWW, 1.37 L and 1.46 L of biogas were produced from 1 L of the substrate used at 25 °C and 37 °C respectively. This shows that biogas production at 25 °C was less by 6.5% when compared to production at 37 °C. This result is comparable to other studies that also established high production of biogas at higher digestion temperatures (Chen *et al.* 2016). The retention time was reduced from 11 days at 25 °C to 8 days at 37 °C, indicating that the activity of anaerobic bacteria was faster at 37 °C than at 25 °C. It is known that biogas production and its methane content normally increase with the increase of temperature.

Effect of modification of municipal wastewater on C/N ratio and total solids

Table 2 shows that SCM was highly biodegradable with 86.71% VS and 17.8% moisture content that suited the dilute nature of the MWW. Moreover, the high C/N ratio of this substrate (64.9) explains the abundance of carbon content that is also suitable for elevating the C/N ratio of MWW. Results from this study showed that only small quantities of the modifier ($\leq$ 10%) were needed to adjust the C/N ratio of MWW from 10.6:1 to 30.4:1. It also caused TS to rise from 2.77% to 10.7%, as shown in Table 3. The use of SCM can largely elevate the C/N ratio and TS compared to many other substrates used in the previous studies for the co-digestion of MWW sludge (Zitomer *et al.* 2008).

Table 3 | Characteristics of the modified substrates

Batch experiments	Amount of modifier (mL) in 1,000 mL of substrate mixtures	C/N ratio	Total solids (%)	Total solids (g/L)	Volatile solids (g/L)
1	0	10.6	2.77	2.23	1.76
2	20	15.7	4.34	10.86	9.24
3	40	20	5.94	19.48	16.72
4	60	23.8	7.52	28.11	24.2
5	80	27.1	9.12	36.73	31.68
6	100	30.4	10.7	45.36	39.17

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The biogas production, yield and methane content at different total solids loading levels

The environment of the microorganisms in the reactor determines the performance of an anaerobic digestion system, because biogas production is directly proportional to the growth of methanogenic bacteria (Chen *et al.* 2012). In the present study, various cumulative volumes of biogas were obtained at different TS levels (Figure 3). The modified substrate of 7.52% TS, corresponding to a C/N ratio of 23.8, had the highest cumulative biogas production while the least biogas production was obtained at 4.34% TS, corresponding to a C/N ratio of 15.7. However, this was 3.4 times higher than the biogas yield from the anaerobic digestion of MWW alone with 2.77% TS and 10.6 C/N ratio. These results are similar to those from another study where the biogas produced from vinasse that had high COD and TS of about 7.02% was also the highest biogas producer (Budiyono & Sumardiono 2014). These results also demonstrate that when the TS are higher than 7.52%, the biogas yields are lower. This is probably due to overloading in the digester, which led to instability of anaerobic digestion and hindrance of methanogenic bacteria digesting the carbons from the feedstock. It should, however, be noted that the optimum loading observed is not universal but depends on the reactor organization and other operating conditions (Dhar *et al.* 2016). Literature also showed that if the amount of TS is high in the digester, there could be over-accumulation of organic matter and blockage of the digestion process. Furthermore, if the amount of water is high, there can be less organic matter in the digester and low biogas production (Liu & Lv 2016). Therefore, for maximum digestion of substrates, the TS must be at an optimal concentration.

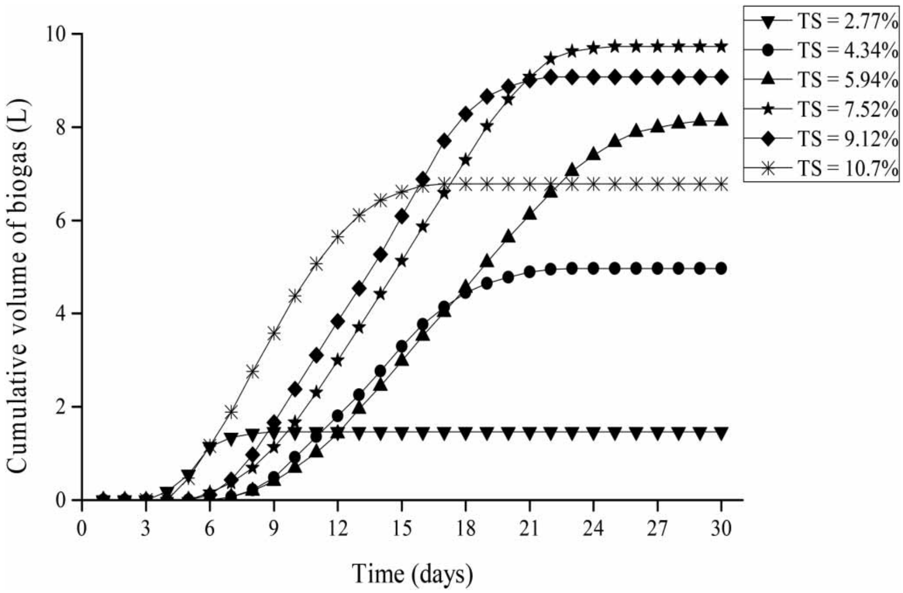

Figure 3 | Cumulative biogas volume at various TS levels as a function of time.

The calculated biogas yield from the modified substrates operated at TS concentrations of 10.7%, 9.12%, 7.52%, 5.94%, and 4.34% were 101, 172, 297,344 and 379 mL/g COD respectively by the end of the digestion process. About 94.8%, 58.1%, 45.4%, 30.1% and 55.7% of total biogas yield were achieved after the first 14 days of digestion. The biogas yields obtained in this study was larger than that obtained from the anaerobic digestion of MWW sludge in studies done by Bougrier *et al.* (2006) and similar to the one obtained from the co-treatment of MWW with food waste. This proves the positive effect of co-digesting MWW for higher biogas yield. Nonetheless, the biogas yield was low compared to the codigestion of MWW with food waste (Guven *et al.* 2019a). There is rare information on codigestion of the raw MWW with other organic waste for biogas production.

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The average methane contents of the produced biogas were 55.6%, 53.3%, 63.1%, 61.7%, 69.1% and 54.2% from 6 modified substrates with 10.7%, 9.12%, 7.52%, 5.94%, 4.34% and 2.77% TS respectively, as shown in Table 4. The biogas content obtained in this study is within the range reported in a comparative review of the sustainability of organic waste management practices in the food-energy-water nexus (Lin *et al.* 2018). The lower biogas and methane yields when the TS concentration was ≥7.52% indicated that there was inhibition of the methanogenic bacteria.

Table 4 | Cumulative biogas volume and its compositions

Batch experiments	Total solids (TS) (%)	Volume of biogas (L/L)	CH_4 (%)	CO_2 (%)	O_2 (%)	H_2S (ppm)	NH_3 (ppm)
1	2.77	1.46	54.2	41.8	0.0	256	6
2	4.34	4.97	69.1	29.9	0.0	215	5
3	5.94	8.13	61.7	38.2	0.0	241	5
4	7.52	9.73	63.1	36.7	0.0	243	4
5	9.12	9.07	53.3	42.4	0.0	260	8
6	10.7	6.78	55.6	43.9	0.0	246	6

The optimal C/N ratio for the co-digestion

The C/N ratio for the optimum production of biogas is known to vary from 20:1 to 30:1 with an optimal value at 25:1 in the mesophilic temperature range (Wang *et al.* 2012). In the present study, the cumulative biogas production was 6.7 times higher at the optimum C/N ratio of 23.8:1 than at the C/N ratio of 10.6:1 of MWW. The higher cumulative biogas production at the C/N ratio of 23.8 was attributed to 94% (v/v) of the MWW and 6% (v/v) of the modifier. The cumulative biogas production increased with the increase of C/N ratio to an optimum value and then decreased (Figure 4). The obtained optimal C/N ratio falls within the range even though it diverts from 25:1, probably because anaerobic co-digestion for higher biogas yield depends upon the type of waste used as co-substrate (Wang *et al.* 2012). The results from other studies show that the optimal C/N ratio of the substrates varies, even though it is very rarely <15 (Iqbal *et al.* 2014). The polynomial curve plot was fitted on the graph with the adjusted R^2 of 92.9%.

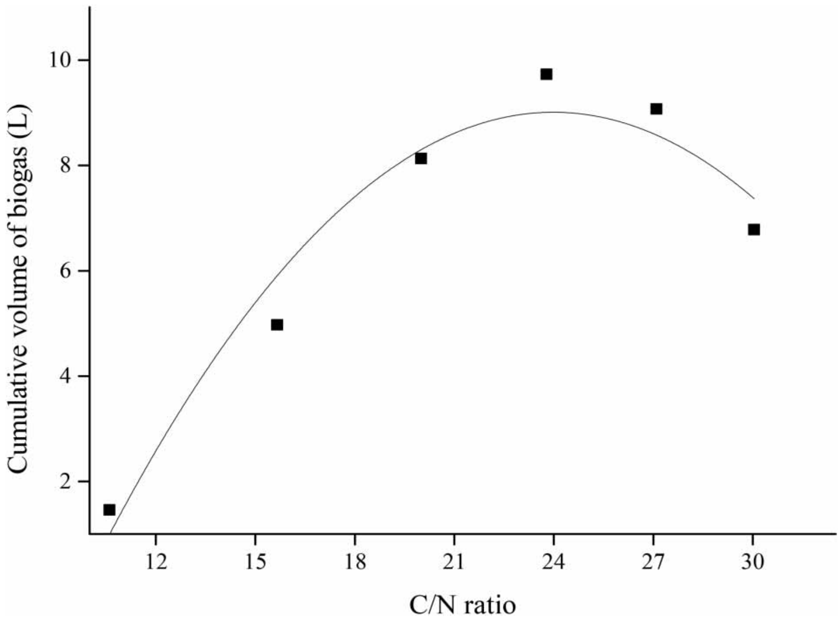

Figure 4 | The maximum cumulative biogas volumes as a function of C/N ratio.

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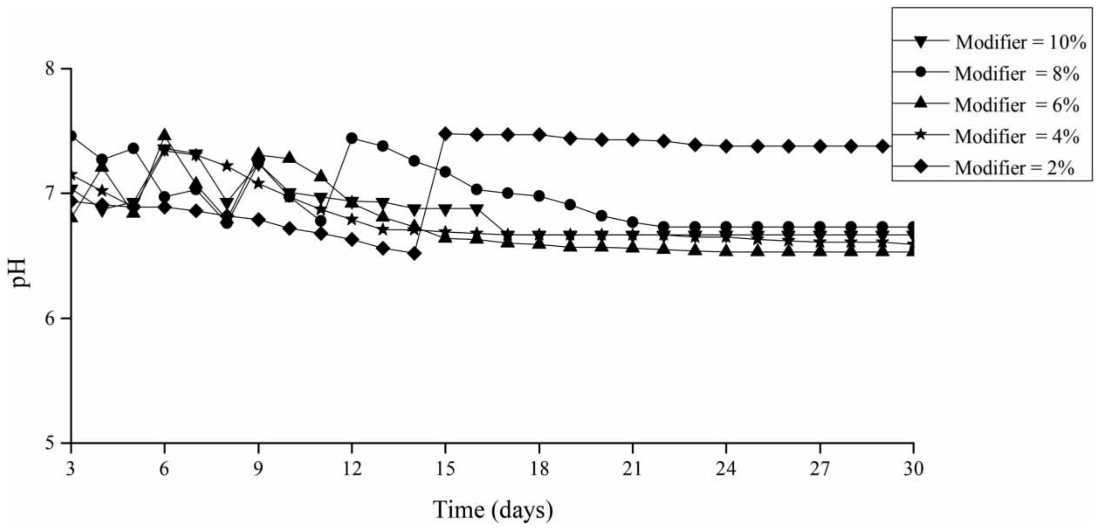

Figure 5 | pH variation at various percentage modifiers.

Effect of modified substrate mixing ratios on the stability of anaerobic digestion

The range of pH and accumulation of VFA in biodigesters are important parameters that determine the stability of the anaerobic digestion process (Chen *et al.* 2012). In this study, Figure 5 shows that the initial pH in the reactors were in the acceptable range at approximately 7.46, 7.37, 7.17, 7.43, 7.47, and 7.30 for 10.7%, 9.12%, 7.52%, 5.94%, 4.34%, and 2.77% respectively. During the anaerobic digestion process, fewer pH fluctuations were experienced in the anaerobic digestion of MWW only with TS of 2.77%, as it was adjusted only once and remained within the permissible range of 6.3–7.8 even at the end of the digestion process. However, for the SCM-modified substrates, pH was observed to increase with increasing TS concentrations. There were high pH fluctuations in the reactors with 7.52%, 9.12% and 10.7% TS which persisted and had to be adjusted until approximately after 14 days, as shown in Figure 5. It should be noted that without pH adjustment, the decrease in pH in modified substrates is enough to affect the methanogenic activities as it dropped below the established minimum suitable range of 6.3–7.8 (Li *et al.* 2015). This indicates the difficulty of producing a high amount of biogas from single-stage anaerobic co-digestion of the substrate used in this study without adjusting the pH. Therefore alkali additional is recommended for pH adjustments in order to minimize hydrolysis and stabilize the methanogenic process.

The results of the present study also showed that VFA/alkalinity of digestate substrates with TS 10.7%, 9.12%, 7.52%, 5.94%, 4.34%, and 2.77% were 1.01, 0.83, 0.82, 0.34,0.11, and 0.23 respectively as shown in Table 5. The VFA to alkalinity ratio for various TS concentrations $\leq$5.94% ranged from 0.11 to 0.34, which indicates the relative stability of the digesters, whereas the substrate mixture with VFA/alkalinity ratio $\geq$0.82 inclined to digester instability. This might be caused by high TS

Table 5 | Levels of acidity and alkalinity in digestate

TS (%)	VFA (mg/L)	Alkalinity (mg/L)	VFA/alkalinity
10.7	2,410	2,386	1.01
9.12	1,974.7	2,370.1	0.83
7.52	1,837.4	2,240.7	0.82
5.94	920.2	2,706.5	0.34
4.34	334.4	3,040.7	0.11
2.77	783.6	3,406	0.23

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concentrations that took a long time for hydrolysis, hence VFA accumulation in the system. This is supported by other studies that suggest the VFA/alkalinity ratio should be maintained below 0.4 for stable anaerobic digestion. Nevertheless, other studies have shown huge variations of optimum VFA between different substrates used in anaerobic digestion (Chen *et al.* 2012). In the present study, alkalinity was in the range of 2,386. to 3,407 mg/L in the reactors (Table 5), it was within the range of 2,000–4,000 mg/L which is required for digesters to perform under stable conditions (Velmurugan 2011). However, the accumulation of VFA to above 920.2 mg/L was sufficient to inhibit the buffering capacity of the alkalinity.

Effect of substrates modification on residual COD

The reduction of COD was examined by considering the level of biodegradability within the reactors. In this study, the COD of the digestate was high in the substrate mixtures with high TS contents and the COD removal efficiency was observed to increase from 10.7%, 9.12%, 7.52%, 5.94% to 4.34%, with the reduction efficiency of 45.83%, 49.62%, 69.2%, 76.69% and 87.02% respectively. The removal efficiency of the substrate mixture with the TS content of 7.52%, 5.94% and 4.34% was observed to be higher compared to 2.77%, as shown in Figure 6. Since the energy capture step in this study is integrated with the treatment of MWW, it is not desirable to have too high a COD residual as it can interfere with further treatment needed for the wastewater to meet environmental compliance standards. The substrate mixture with 4.34% TS was recommended because of its lesser pH fluctuations and lower COD residue in the effluent (1.8 g/L), which will be treated further within the WSPs system used in the WWTP. Also its removal efficiency of 87.02% is higher compared to the other study on co-treatment of municipal wastewater and food waste where a maximum of 63% COD removal was achieved (Guven *et al.* 2019a). The higher residual COD was probably due to the accumulation of high levels of organic materials in the biodigester. As a result, methanogens can be inhibited through overproduction of VFA in the anaerobic reactor (Dhar *et al.* 2016).

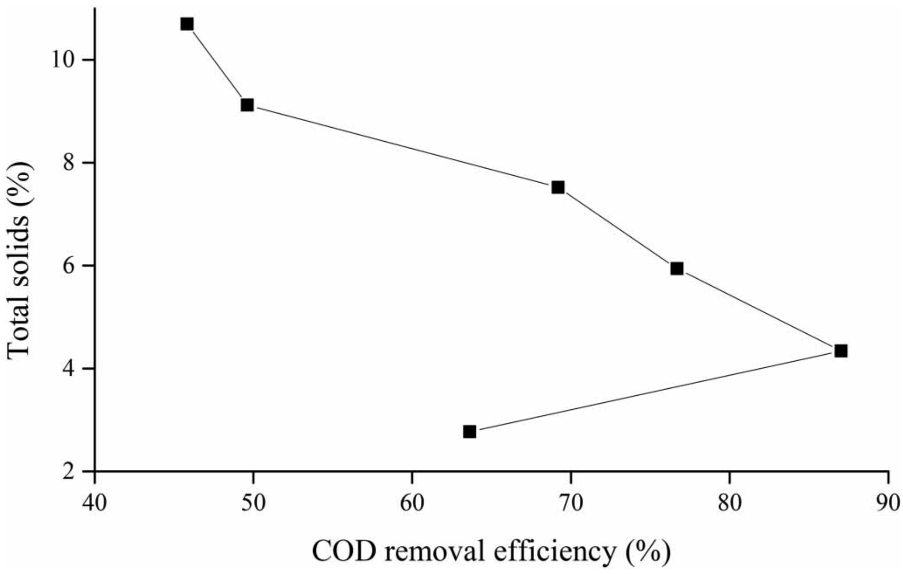

Figure 6 | Correlation of the TS (%) and COD removal efficiency (%).

Estimation of energy recovery from anaerobic digestion of modified Moshi municipal wastewater

The estimation of the potential heat and electricity production from the biogas was calculated from the results obtained from the anaerobic digestion of the modified substrate with 4.34% TS and 15.7 C/N ratios due to the aforementioned reasons. The average daily inflow was 4,221 m^3/d. The

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Table 6 | Estimation of annual heat and electricity production from the produced biogas

Data needed	Value	Source/basis
Average daily amount of the MWW received	4,221 m^3/day	Measured flow rate (MUWSA)
Total daily SCM needed	92.9 m^3/day	Mixing ratio of 2% v/v in substrate mixture
Biogas production from 1 batch reactor	23,537 m^3	1 L of substrate mixture produces 4.97 L of biogas
Energy content of pure methane	Heat energy = 39.8 MJ/m^3 Electrical energy = (11.06 kWh/m^3)	Jørgensen (2009)
Average methane content of the generated biogas	69%	Mixing ratio of 2%v/v in substrate mixture
Heat energy efficiency of CHP engines	45–50%	Jørgensen (2009)
Electrical energy efficiency of CHP engines	35–40%	

information used for the estimation of the possible daily electricity and heat production is shown in Table 6.

The Moshi municipal wastewater treatment system with an annual generation of the modified substrate of 662,973 m^3 is anticipated to generate about 16,241 m^3 of methane through anaerobic decomposition. If gas turbines which use combined power and heat engine (CHP) with the efficiency of 35% are used, then about 1.8 GWh/year could be produced. A 5MW CHP engine with 10 working hours per day could be installed with such amount of electricity. The estimated amount of electricity was smaller compared to the 79 GWh/year produced from sisal waste generated annually in Tanzania (Mshandete *et al.* 2006). Also to the 14 GWh/year which estimated from co-treatment of municipal wastewater and food waste as reported by Guven *et al.* (2019b). However, it was not far from the 2.4 GWh/year obtained from the waste produced by Serengeti breweries (Nassary & Nasolwa 2019). These differences might be caused by the conversion technology used which reflected electrical energy only and not with thermal energy as it was considered in this study, conversion efficiency considered and the methane yield which varies from one feed stock to another. The produced electricity estimated in this study can reduce the energy demand in the country based on the fact that Tanzania is electrical energy-deficient with plans to increase the installed power capacity from 1,564 MW to about 10,000 MW by 2025. Even though many studies do not consider the production of thermal energy in biogas plants, itt is the valuable energy for water or space-heating to maintain the mesophilic or thermophilic temperatures for enhancing the optimal production of biogas.

CONCLUSION

The present study reveals the possibility of using small quantities of a modifier with a high C/N ratio to improve the biogas yield from MWW anaerobic digestion. The highest biogas production (9.73 L/L of modified substrate) was obtained from the substrate mixture with 6% of SCM as a modifier. High COD of the digestate and pH instability was the main challenge. This study recommends the use of substrate mixture containing modifier (2%), TS (4.34%) and C/N (15.6) with the biogas production (4.97 L/L of modified substrate). Its lower COD (1.8 g/L) of digestate, low pH fluctuation and low VFA /alkalinity ratios support its recommendation since the aim was to integrate an energy recovery step with MWW treatment. Consequently, this output can be treated easily with the available WSPs. The produced biogas was estimated to produce 16,241 m^3 of methane, which is equivalent to 1.8 GWh and 8,193 GJ per annum. This showed biogas from MWW is among the impending fuels if the modern technology and ideas on its production and use are applied. Conclusively, there should be encouragement to the government and private investment in MWW treatment, which

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combined with anaerobic digestion for electricity generation is needed due to the fact that the renewable energy policy aligns with the available policy worldwide.

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DATA AVAILABILITY STATEMENT

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

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