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Estimation of methane generation based on anaerobic digestion and mass balance at Kiteezi Landfill, Kampala, Uganda

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Kiteezi landfill site is the main solid waste dumping site in Kampala City (Uganda). In this study, the generation of methane from waste at Kiteezi landfill was measured using laboratory-scale anaerobic digestion experiment and estimated using the Mass balance model. The samples were collected in the wet and dry seasons, with five replicates for each season which were processed for further experiments focused on moisture content analysis and anaerobic digestion. The moisture content analysis results showed a significant change ($P < 0.05$) between wet season and dry season. Also, the anaerobic digestion revealed that moisture content was a determining factor in gas generation. The average monthly methane production estimate from the mass balance model was 1.63 Gg methane/month and was comparable (within 14%) to the amount estimated by laboratory-scale anaerobic digestion experiment (1.43 Gg methane/month). It is a worthwhile undertaking to further investigate the potential of commercially producing methane from Kiteezi landfill as an alternative source of green and clean energy for urban masses.

Key words: Solid waste management, methane generation, anaerobic digestion and mass balance model.

INTRODUCTION

Kampala Capital City Authority (KCCA) is in charge of solid waste (SW) management. Kampala is approximately 199 km^2 with a population of over 2 million at a population growth of 3.9% (UBOS, 2012). About 28,000 tons of the waste is delivered monthly to Kiteezi landfill, but this is only 40% of the overall waste generated in Kampala (Komakech et al., 2014). The uncollected garbage is dumped on the streets, drainage and water channels and unoccupied land causing environmental and health challenges (Komakech, 2014). KCCA is in charge of collection, transportation and disposal of municipal waste to the landfill. The landfill is situated on 29 acres in Kiteezi. However KCCA still faces a challenge on how to manage the waste effectively and appropriately. This is due to inadequate data such as; estimated amount of refuse projected to be generated and collected per day, the average composition of solid waste and number of households within Kampala (Anon,

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2010; Anesa et al., 2006). Other challenges KCCA faces include; inadequate sorting of waste, poor sensitization of the public, poor urban planning, few sites for dumping, lack protective gears when sorting and collecting the waste. This leads to the preparation of work plans and budgets that do not adequately address the challenges in solid waste collection, transportation and disposal (Anon, 2010; Anesa et al., 2006). The amount of waste and its composition received at the landfill varies quite often due to the seasonal variations, weather, cultural practices, methods and frequency of waste collection, food habits, waste burning and the scavenger's activity. However, at the landfill the SW vehicles are no longer weighed but quantities are estimated on the basis of the number of disposals made by the SW vehicles, this is not at all reliable since there are changes in the compactness of the SW. Hence, it is problematic to estimate the amount and composition of waste reaching the landfill site. The municipal solid waste (MSW) handled at the landfill consists of degradable waste (textile, textiles, paper, food waste, yard waste), partially degradable waste (wood, disposable napkins) and non-degradable materials (synthetic and non-synthetic polymers). There are worries over health concerns from such a landfill site, including skin cancer, birth defects, mortality, and low birth weight (WHO, 2007) in addition to other environmental problems, which are as a consequence of greenhouse gas (GHG) emissions. Methane gas which is the main GHG liberated from landfills is a big threat to our environment, because its global warming potential is 25 times of that of carbondioxide (CO_2) (Solomon et al., 2007) and is at least 56 times more heat-trapping than a molecule of carbon dioxide (Nakibuuka et al., 2012). Methane generation from landfills is projected to account for 3-19% of the anthropogenic sources in the world (Kumar et al., 2004). Although, on the contrary solid waste management is not put into consideration that much and maintenance of record is poor, in Uganda. The aim of this research was to quantitatively estimate the methane generation at Kiteezi landfill.

METHODS AND MATERIALS

Study area

The study was carried out at Kiteezi landfill located north of Kampala, approximately 12 km from the city centre, in Wakiso district, central Uganda. The landfill is accessed from Kampala city through Kampala-Gayaza road about nine (9) km, then branch off to the left at Mpererwe into Namere road. It was opened in 1996, and has a spatial extent of about 29 acres (Mugisa et al., 2015). All waste received is heaped and later compacted in layers within a confined area and covered according to the practical requirements and content aspects the cover material.

Sample collection and analysis

The solid waste samples were collected for three months in a period that covered both dry and wet seasons with five replicates

for each season. Characterization of the samples followed a procedure described by Komakech et al. (2014).

Moisture content was determined by drying 10 g for each waste sample at 105°C for 4 h following the method explained by Sluiter et al. (2008). The average moisture content for the five replicates was taken as the sample moisture content. To determine generation of methane by field measurements, a one (1) kg waste sample was taken to the laboratory for anaerobic digestion (Plate 1). The procedure described by Glenn et al. (1989) was followed to estimate methane gas generation by the anaerobic decomposition of waste.

Methane estimation by mass balance models

IPCC models (2006), viz. mass balance (Equation 1) was used for estimating methane gas at Kiteezi landfill. By knowing the monthly waste flow records reported in literature and using default values as presented by the IPCC guidelines of 2006, the methane generation was estimated at Kiteezi landfill.

$$\text{Methane}\left(\text{GgCH}_4/\text{month}\right) = M(x) \times L_0(x) \tag{1}$$

Where, M(x) is the monthly waste acceptance to the landfill site x under study (Gg/month) and $L_0(x)$ = ultimate methane yield (Gg methane/Gg waste).

$$L_0(x) = \text{MCF}(x) \times \text{DOC}(x) \times \text{DOC}_F \times F \times \frac{16}{12} \tag{2}$$

Where, MCF(x) is the methane correction factor in a month x, DOC(x) is the degradable organic carbon in a month x (Equation 3), DOC_F fraction of DOC dissimilated a function of average ambient temperature (Equation 4), F is the fraction by volume of methane in landfill gas, and $\frac{16}{12}$ is the conversion of carbon to methane.

$$\%\text{DOC}(\text{by.weight}) = 0.4(A) + 0.17(B) + 0.15(C) + 0.3(D) \tag{3}$$

Where, solid waste composition consists of: A = % paper and textile, B = % garden and park waste, or other organic putrescible, C = % food waste; and D = % wood or straw.

$$\text{DOC}_F = 0.014(T) + 0.28 \tag{4}$$

Where, T is the average temperature at Kiteezi landfill.

RESULTS AND DISCUSSION

Municipal solid waste (MSW) characterization

Based on the physical composition of waste, different waste samples showed no significant differences (P>0.05) in the organic, hard plastics, metals, papers and soft plastics solid wastes. The mean percentage of waste composition are presented in Figure 1. The high variation in organic waste composition especially from residential and market zones is unique to Kampala, but makes it

Plate 1. Laboratory experimental setup for the generation and collection of methane gas.
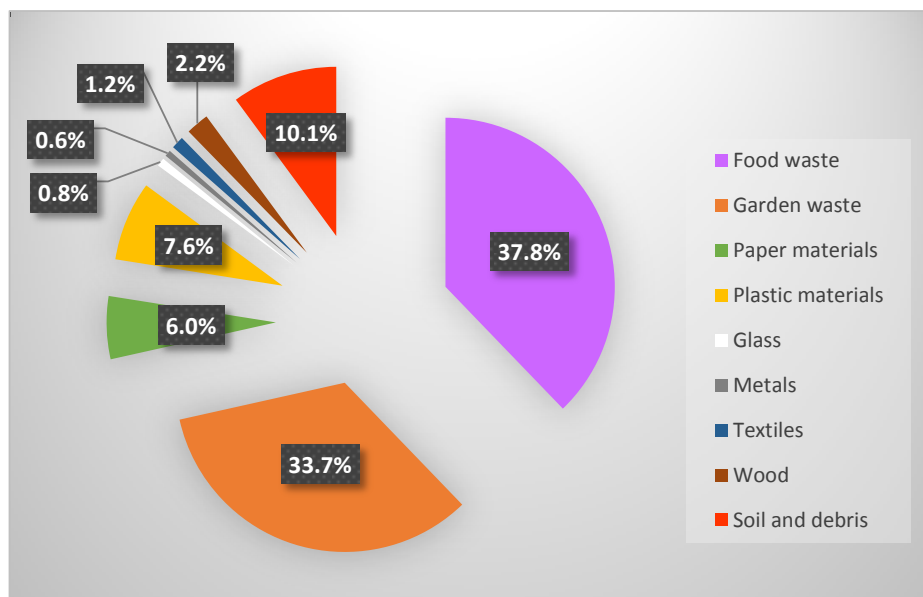

Figure 1. Mean percentage composition of municipal solid waste.

suitable for anaerobic digestion and hence production of landfill gas. Therefore studies assuming average values of organic waste for Sub-Saharan African (SSA) cities, may provide erroneous results in estimating methane generation. Indeed the results of this study are different from those reported from other SSA cities like Gaborone

Table 1. Measured Municipal solid waste moisture content.

Treatment	Rep 1 (MC), %	Rep 2 (MC), %	Rep 3 (MC), %	Average (MC), %
T1	90	96	87	91.0±4.6
T2	56	52	64	57.3±6.1

Mean±standard deviation, %dry basis.

(Bolaane and Ali, 2004), Abuja (Imam et al., 2008) and Accra (Fobil et al., 2008) in part explained by the intrinsic relationship of the solid waste content to the population lifestyle.

Total tonnage of waste entering the landfill

From a study conducted between July 2011 and June 2012, an average mass of approximately 28,000 tons of municipal solid waste from Kampala was dumped at Kiteezi landfill every month (Komakech et al., 2014). There was no significant difference (P > 0.05) in the waste quantities disposed at Kiteezi during the different months. However, the months of March to June had waste quantities higher than the average.

Moisture content of MSW

The municipal solid waste moisture content for each treatment is summarized in Table 1. The moisture content of waste influences the rate of decomposition and gas generation. Therefore more gas was generated from wetter waste sample than the dry waste sample. Abundant availability of oxygen molecules in water inhibits methane production. One way ANOVA showed no significant difference among replicates within treatment T1 and T2 (P > 0.05). However, a significant difference (P < 0.05) between Treatment T1 and T2 was observed.

Estimation of methane generation

The average estimated values of landfill gas from the laboratory scale anaerobic digestion generated in the wet and dry seasons are shown in Figure 2. The composition of methane in the landfill gas was determined following procedure described by Hedge et al. (1994), and the methane generation is depicted in Figure 3. Using one-way ANOVA, results showed significant differences (P < 0.05) in the gas generation due to seasonal variation. Specifically, 57 ml landfill gas/kg waste was produced at moisture content of 91.0% dry basis. Our methane gas estimates and measurements agree with those of Burton et al. (2005) findings when moisture content of the samples is taken into account.

The time taken for gas production to cease was 360 hwith only 0.04 Kg out of 1 Kg waste sample decomposed. This implied that a cumulative amount of waste of 2.2 Kg decomposed and generated 220.2 ml of methane gas in a 10 day period. Consequently 300.27 ml of methane gas was generated from 1 Kg of waste sample within a month. Using, approximately 28,000 tons of municipal solid waste from Kampala that is dumped at Kiteezi landfill every month, the corresponding volume of methane gas generated is 3.36×10^9 ml. Considering the density of methane is 0.4256 g/ml, the equivalent mass of methane produced on a monthly basis is 1.43 Gg.

Methane estimation based on mathematical modelling was done based on Equations (1) of the Mass balance model. Where, M(x) was the waste received to the landfill in a month x. MCF was taken as 0.8 for unmanaged deep landfill site (greater than 5 m), based on composition of waste for Kampala, DOC value was calculated (Equation 3) to be 0.142. The value for dissimilated organic fraction (DOC_F) using a temperature of 35°C was calculated (Equation 4) to be 0.766 and the average default value of the fraction of methane in LFG (F) was taken as 50%. Since no methane has ever been recovered from the landfill, the value for methane recovery factor and oxidation factor was taken to be zero and was not included in the models. The monthly methane production values calculated are shown in Table 2.

The average monthly methane production estimate from the mass balance model (1.63 Gg methane/month) was comparable (within 14%) to the amount estimated by laboratory-scale anaerobic digestion experiment (1.43 Gg methane/month). The difference may be explained by the selected fraction of methane in LFG (F) and unaccounted for emission paths in the anaerobic digestion experiment. From their study (Kyambadde et al., 2006), on Kiteezi landfill, in a report he submitted to National Environment Management Authority (NEMA), the estimated methane production was 1.44 Gg/ month and this is comparable to the methane estimates in this study.

Conclusions

Solid waste disposed at Kiteezi landfill mostly comprised of bio-degradable waste which has high methane gas production potential. In this study, the estimated methane values using mass balance model were comparable to those of the anaerobic digestion. It was observed that
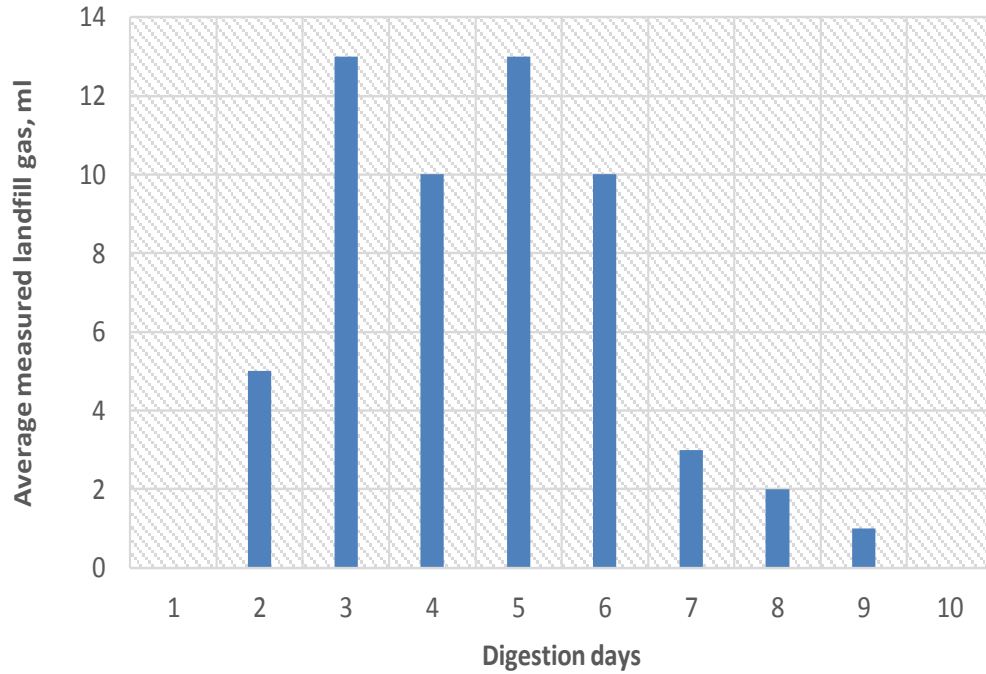
Figure 2. Landfill gas estimations using laboratory scale anaerobic digestion.
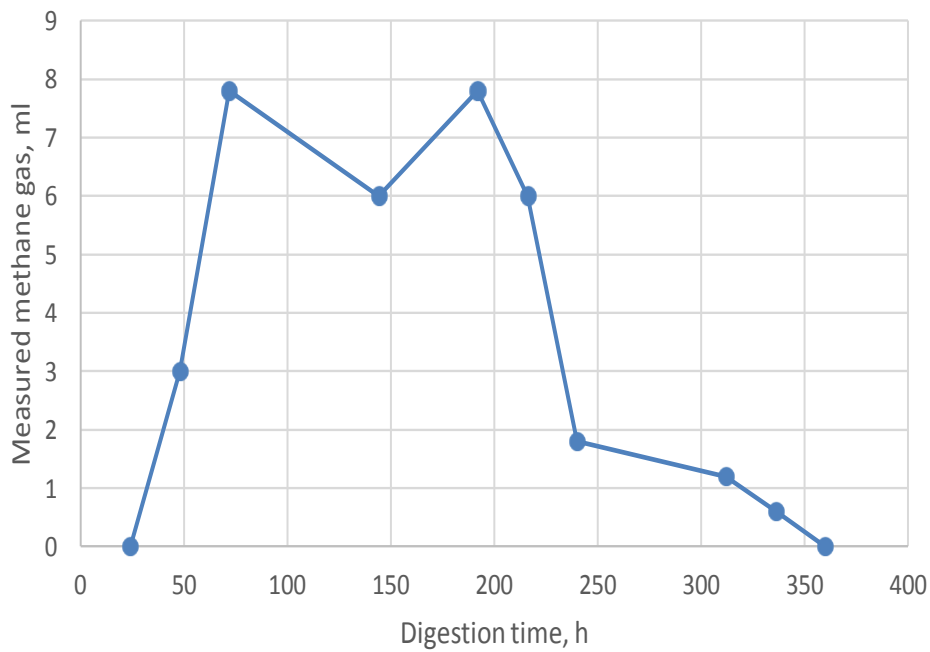

Figure 3. Methane gas estimations using laboratory scale anaerobic digestion.

moisture content has a substantial effect on reducing methane gas production during the anaerobic decomposition of refuse due to abundant availability of oxygen molecules. The rate of gas production, and total gas production increased at lower moisture contents.

Given the volume of methane gas estimated, energy recovery process for electricity production using the methane generated from landfill as natural resource is recommended. However, assessing individual or composite categories of organic waste in Kiteezi landfill

Table 2. Methane estimations using the mass balance model.

Year	Month	M(x) (Gg waste/month)	Lo(x) (Gg methane/Gg waste)	Methane generated (Gg methane/month)
2011	July	27.9	0.058	1.618
2011	August	27.6	0.058	1.601
2011	September	26.8	0.058	1.555
2011	October	27.1	0.058	1.573
2011	November	27.9	0.058	1.619
2011	December	27.0	0.058	1.567
2012	January	28.0	0.058	1.628
2012	February	27.0	0.058	1.567
2012	March	29.3	0.058	1.699
2012	April	29.7	0.058	1.723
2012	May	29.5	0.058	1.711
2012	June	29.5	0.058	1.711
Average		28		1.630

to determine their methane potentials, developing Monte Carlo Simulations (Stochastic Analysis) for Kiteezi landfill, and performing gas chromatography experiments at Kiteezi landfill site should be done to achieve accurate estimations of methane gas.

Conflicts of interests

The authors have not declared any conflict of interests.

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