Nigerian Journal of Technology (NIJOTECH)
Vol. 38, No. 3, July 2019, pp. **784 – 791**

Print ISSN: 0331-8443, Electronic ISSN: 2467-8821
www.nijotech.com
http://dx.doi.org/10.4314/njt.v38i3.34

A MODEL FOR THE ACCURATE ESTIMATION OF METHANE EMISSIONS IN LANDFILLS

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ABSTRACT
Landfills are one of the major sources of methane (CH_4) emissions. Prediction of CH_4 emissions from landfills is important in estimating power generation potential and greenhouse gas (GHG) emissions from landfills. The most widely used landfill gas (LFG) models developed based on the first order decay (FOD) reaction do not take into account changing waste composition and landfill site conditions in methane estimations. The aim of this study was therefore to develop a LFG model for estimation of methane emissions from landfills in Lagos metropolis. Field investigations were carried out to determine waste composition, waste disposal rates and site conditions relevant for methane emissions estimation. Waste composition studies were conducted and waste fractions were divided into rapidly, moderately and slowly degrading. The output of the model was verified with the US EPA Landfill Gas Emission model (Land GEM). Results revealed maximum CH_4 emissions estimated occurred at the end of landfill's closure. Methane generation potential (L_o) and methane generation rate (k) parameters were dependent on waste composition and site conditions. Model verification also showed methane emissions peaked at the end of landfill's closure for both models and variation in modelling parameters by Land GEM model resulted in significant change in methane emissions.

Keywords: *Methane emissions, Landfills, Municipal solid waste, landfill gas, Land GEM model*

1. INTRODUCTION

Urban population of the world has grown rapidly from 751 million in 1950 to 4.2 billion in 2018.Asia, despite its relatively lower level of urbanization, is home to 54% of the world's urban population followed by Europe and Africa at 13% each [1]. Waste volumes are expected to grow faster than the rate of urbanization with the volume increasing to 2.2 billion tonnes by 2025 [2]. Disposal of waste in landfill continues to be the most economically viable municipal solid waste (MSW) management practice in many countries in the world [3]. Landfill sites containing wastes undergoing biological decay typically emit high volumes of landfill gas (LFG). LFG mainly consists of 45% to 60% methane (CH_4), 40% to 60% carbon dioxide (CO_2) and small amounts of nitrogen, oxygen, ammonia, sulphides, carbon monoxide and non-methane organic compounds (NMOC) such as trichloroethylene, benzene and vinyl chloride [4]. Approximately 70% of CH_4 emissions are anthropogenic and 19% of these are attributed to LFG generation [5].

The establishment of sustainable landfills is a key strategy in modern waste management concepts [6] and to evaluate appropriate methane reduction strategies, LFG production rates must be accurately quantified [7]. A large number of numerical and mathematical models have been developed to estimate LFG based on zero, first, and second-order approaches. However, zero and second-order models are not commonly used because the required parameters in each model are often so uncertain that

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they negatively affect the accuracy of the model outcomes. Because of these limitations, simplified approaches have been developed based on first-order waste decay (FOD). The FOD models widely used by industry and state regulators are the Intergovernmental Panel on Climate Change (IPCC) and the United States Environmental Protection Agency Landfill Gas Emission Model (US EPA Land GEM) [3]. Most of these models are based on two primary model parameters, an ultimate methane generation potential (L_o) and a first-order decay rate constant (k) . Estimation of these parameters is challenging because they are affected by many factors including, among others, the amount of waste disposed, waste composition, moisture content, temperature, and lag time in gas generation [8]. Current landfill gas generation models are typically overly simplified, not accounting for landfill-specific variations in waste composition, moisture content, and ambient temperature, which can significantly impact methane generation rates [9]. For instance, the widely used Land GEM has k and L_o values fixed over the entire life of a landfill. It doesn't accommodate changing landfill conditions such as variation in waste composition, climatic conditions and applications of liquid to existing waste. A number of international LFG models have been developed for countries such as Mexico, Ecuador, China, Ukraine and Columbia under the US EPA Landfill Methane Outreach Program (LMOP).These models are based on the Land GEM FOD and have model parameters k and Lo dependent on the climatic conditions and landfill site conditions of these countries.

Waste generated in Lagos state increases with population and industrial development, with about 13,000 metric tonnes of municipal solid waste (MSW) generated daily. Wastes are collected and disposed at non-engineered landfills located at Ikeja (Olushosun) and Alimosho (Abule Egba and Solous) local government area respectively [10]. These sites lack adequate design consideration and have technical and operational problems, thereby functioning as dumps for municipal, healthcare and industrial waste materials [11]. Release of LFG has led to greenhouse gas (GHG) emissions and fire outbreaks due to open burning of refuse. Accurate prediction of LFG volumes in these landfills is needed in order to reduce modelling errors as well as under/over estimation of LFG recovery systems. Literature information is scarce on availability of LFG models for the estimation of CH_4 generation in Lagos landfills. The aim of this research is therefore to develop a LFG model for the estimation of CH_4 generation in landfills in Lagos Metropolis.

2. METHODOLOGY

2.1 Model Development

The model estimates CH_4 generation based on FOD methodology in Land GEM model [12]. The model parameters k and L_o were modified using the IPCC methodology [13]. The modified equation is described in Equation 1:

$$Q_{CH_4} = \sum_{i=1}^{n} \sum_{j=0.1}^{1} kL_o \left[\frac{M_i}{10}\right] e^{-kt_{i,j}} \, (FDF) \qquad (1)$$

where

Q_{CH_4} = estimated methane generation rate (m^3/yr)

i = 1 year time increment

n = (year of calculation) – (initial year of waste acceptance)

j = 0.1 year time increment

k = methane generation rate constant (yr^{-1}),

L_o = methane generation potential of waste disposed (m^3/tonne)

M_i = solid waste disposed in the year i^{th} year (tonnes)

$t_{i,j}$ = age of the j^{th} section of waste disposed in the i^{th} year (decimal years)

FDF = fire discount factor

In order to avoid the use of excessive Excel worksheets as applicable in Land GEM model and allow flexibility in varying model parameters L_o and k. The new model was developed with MATLAB Applications. The model allows the user input respective waste composition, waste depth, waste temperature, waste disposal rate and fire discount factor applicable to individual landfill.

2.2 Methane generation potential (L_o)

This describes the total amount of CH_4 potentially produced by a metric tonne of waste as it decays. CH_4 generation was calculated by IPCC methodology [13] as shown in Equation 2:

$$L_o = DOC \times DOC_f \times MCF \times F \times {}^{16}/_{12} \qquad (2)$$

DOC: is the organic carbon in waste that is accessible to biochemical decomposition. DOC values for various waste components [13] are shown in Table 1. This is multiplied by the percentage of the waste fraction in MSW.

Table 1: DOC content for different MSW components

S/N	Waste components	DOC content in (%) of wet waste
A	Paper and textile	0.4
B	Garden and park	0.17
C	Food waste	0.15
D	Wood	0.30
E	Plastics, Metal, Glass and other inert materials	0

Source [13]

Table 2: MCF values for various landfill sites

Landfill site	Depth < 5m	Depth ≥ 5m
Without management	0.4	0.8
With management	0.8	1.0
Semi aerobic	0.4	0.5
Condition unknown	0.4	0.8

Source [13]

F

DOC_f: This is an estimate of the fraction of carbon that is ultimately degraded and released from solid waste disposal sites (SWDS), it reflects the fact that some degradable organic carbon do not degrade, or degrades very slowly, under anaerobic conditions in the SWDS. This depends on the temperature in the anaerobic zone of the landfill site [14, 15]. The DOC_f is expressed in Equation 3

$$DOC_f = 0.014T + 0.28 \quad (3)$$

where T is temperature in the anaerobic zone in °C. If unavailable by the user, a default value of 35°C was used. At 35°C, almost 80% of the DOC would have been converted to LFG [14].

MCF: This is the methane correction factor which takes into account aerobic waste decay that does not produce CH_4 at waste disposal sites [13]. It depends on the depth of a landfill and ranges from 0.4 – 1.0 (Table 2).

F**:** This is the fraction of CH_4 in LFG [13, 15].A value of 50% was adopted.

2.3 Methane generation rate constant (k)

This describes the time taken for the DOC in waste to decay to half its initial mass. It is called half-life and denoted by k. The rate at which CH_4 emissions are generated from decaying material in a landfill depends upon: (1) the waste type (organic material placed in the landfill), and (2) the moisture conditions of the landfill (estimated based on average annual precipitation). The waste fractions were divided into three waste categories based on their rate of decay as: rapidly-degrading waste, slowly degrading waste and moderately degrading waste. These three waste categories were assigned different k values to reflect their differences in waste decay rates based on their climatic conditions (Table 3). The k value used in the model was then calculated by multiplying the different k values by the quantity of the waste category in the waste stream and an overall k value for a mixed municipal solid waste was gotten.

2.4 Fire Discount Factor (*FDF)*

The model also introduced the fire discount factor (FDF) in order to account for occurrence of landfill fires. For landfills where current or past landfill fires have been observed or are likely present, a reduction of 20 to 40% in the methane estimate might occur as the combined result of loss of organics and damaged collection system. For landfills where current or past landfill fires have been observed, fire discount factor is set at 30% [16].

Table 3: Methane generation rate constant for different wastes

S/N	Type of waste	Decay Rates (k)			
		Dry		Moist and Wet	
		MAT<20°C	MAT>20°C	MAT<20°C	MAT>20°C
1	Rapidly degrading waste (food waste)	0.05-0.08 Default:0.06	0.07-0.10 Default:0.085	0.10-0.20 Default:0.185	0.17-0.70 Default:0.4
2	Moderately degrading waste (garden + park)	0.04-0.06 Default:0.05	0.05-0.08 Default:0.065	0.06-0.10 Default:0.1	0.15-0.20 Default:0.17
3	Slowly degrading waste (paper+ textiles)	0.03-0.05 Default:0.04	0.04-0.06 Default:0.045	0.05-0.07 Default:0.06	0.06-0.085 Default:0.07
	Slowly degrading waste (wood and straw)	0.01-0.03 Default:0.02	0.02-0.04 Default:0.03	0.02-0.04 Default:0.025	0.03-0.05 Default:0.035

Source [13]

2.5 Description of Study Area

Olushosun Landfill: It is the largest landfill in the state and is situated about 10km South East of Ikeja Local Government Area, and located between 6º59'11.11N 3º38'13.89E [17]. It was established in 1992 with a lifespan of 35 years from the date of its establishment. It received an average of 1,000,000 tonnes of waste annually [18]. The landfill was recently closed in June, 2018 due to fire incidence. The climate of the landfill location is similar to Lagos metropolis climate and is characterized by rainy and dry seasons. The monthly mean temperatures of the landfill ranged from 25.2 °C-28.6 °C. The temperature is highest in March, at 28.6 °C and lowest in August at 25.2 °C. Average precipitation also ranged from 21 mm – 386 mm. The least amount of rainfall occurs in December at about 21 mm while the greatest amount of precipitation occurs in June, with an average of 386 mm. The average annual precipitation is 1693 mm [19].

2.6 Waste disposal rate

Waste disposal in Olushosun landfill started in 1992 till March, 2018 when it was closed by the Lagos State government due to the fire incidence. The landfill received approximately 40% of the total waste deposits in Lagos state [20]. Waste deposited in the landfill consisted of unprocessed wastes of all types, ranging from organic to inorganic and hazardous to non-hazardous wastes. The quantity of waste deposited in the landfill had been on the increase due to rapid population growth and urbanization. Waste deposited in the landfill increased from 165,909 metric tonnes in 1992 to 880,866 metric tonnes in 2017. A total of 11,066,908 metric tonnes of wastes was deposited in the landfill at the time of closure (Table 4).

2.7 Waste composition

Sampling of wastes was carried out at Olushosun landfill in the dry and wet seasons (April, 2015 and July 2016) according to American Society of Testing and Materials (ASTM-D5231-92)[21]. The duration of the studies and sample sizes were different for the two seasons due to the on-going renovation at the site at the time of investigation. In the dry season, a total of 40 trucks were sampled for a period of 6 days while 74 trucks were sampled for 14 days during the wet season. Bags of wastes of about 200 kg were picked randomly from each compactor trucks tipping at the site during both seasons, the sampled wastes were placed on a mat, opened and remixed until a representative sample of 100 kg was obtained. Characterization of the waste samples followed a procedure described by [22].

3. RESULTS AND DISCUSSION

3.1 Waste composition studies

The results of the waste composition studies showed that waste collected in Lagos metropolis and deposited in Olushosun landfill contained about 50% food waste while 45% were recyclable waste (Figure 6).

Table 4: Waste disposal rate in Olushosun landfill

Year	Waste deposited (metric tons)	Cumulative waste deposited (tons)	Year	Waste deposited (metric tons)	Cumulative waste deposited (tons)
1992	165909	165,909	2005	312846	3,251,584
1993	174204	340,113	2006	328489	3,580,073
1994	182914	523,027	2007	344912	3,924,985
1995	192060	715,087	2008	567814	4,492,799
1996	201663	916,750	2009	596205	5,089,004
1997	211746	1,128,496	2010	626015	5,715,019
1998	222333	1,350,829	2011	657316	6,372,335
1999	233450	1,584,279	2012	690181	7,062,516
2000	245123	1,829,402	2013	724690	7,787,206
2001	257379	2,086,781	2014	760925	8,548,131
2002	270248	2,357,029	2015	798971	9,347,102
2003	283760	2,640,789	2016	838920	10,186,022
2004	297949	2,938,738	2017	880866	11,066,908

Source [10]

This is also confirmed by various waste composition studies conducted in the state (Table 5) which indicated that solid waste generated is mostly organic consisting of food waste [22-24]. The proportion of some of the recyclable fractions was relatively small (such as metals - 4%, glass - 2% and plastics - 7%). This was a result of scavenging activities being undertaken at the disposal site.

Waste composition studies in Lagos State from previous years were collated, and the average was established. (see Table 5). This was used in the determination of k and L_o values used in the estimation of methane emissions.

3.2 Methane emissions estimation from Olushosun landfill

Estimation of methane emissions for Olushosun landfill was done for the period 1992-2020.The following data was used to estimate methane emissions:

- *DOC* value was found to be 0.19 based on the waste composition of MSW deposited in the landfill
- DOC_f was found to be 0.77 by assuming a landfill temperature of 35°C
- *MCF* for Olushosun landfill was 0.8 as this satisfied the criteria of an unmanaged deep landfill
- *FDF* was 30% due to open burning of refuse that had been practiced

Based on the estimation of different parameters, L_o of 76.36 m^3/ton was derived for Olushosun landfill. This value is within the range of 6 – 270 m^3/ton specified by US EPA, but L_o varies across different landfills in different countries [8]. $L_o$values of 90 – 128 m^3/ton was recorded for 35 Canadian Landfills with the use of European Pollutant Emission Register (EPER), Netherlands Organisation of Applied Scientific Research (TNO), Zero-order, Scholl Canyon and LandGEM version 2.01 models [7]. Results from [25] also indicated L_o value of 43.01 m^3/tonne at Awotan and Lapite dumpsites in Ibadan, Nigeria. This value was lower than methane generation potential for Olushosun landfill due to low organic waste deposited. $L_o$value depends almost exclusively on the waste composition and it is a function of the organic content of the waste. The higher the organic content of the waste, the higher the L_o [26].

In order to estimate k value for the landfill, the suggested default values of k for different waste categories for a wet landfill at temperature greater than 20°C was used. k value of 0.24 yr^{-1}was derived for Olushosun landfill.

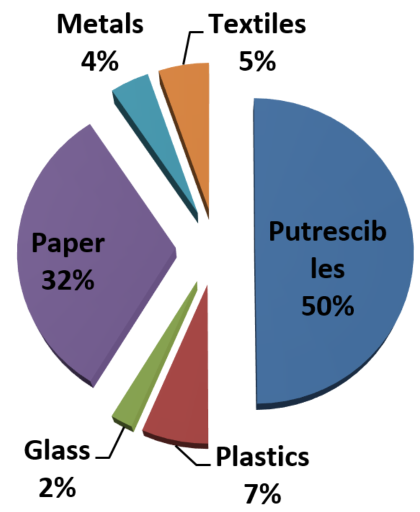

Figure 1: Composition of MSW generated in Olushosun landfill

Table 5: Waste composition studies in Lagos Metropolis

Waste composition (%)	Longe and Ukpebor (2009)	Ogwueleka (2009)	Oyelola and Babatunde (2010)	Present study	Average
Putrescibles	41.8	56	68.57	50.88	54.31
Plastics	7.8	4	2.71	6.72	5.30
Glass	9	3	1.78	2.25	4.00
Paper	16	14	16.95	32.48	19.85
Metals	7.4	4	2.97	4.2	4.64
Garden	0	0	4.20	0	4.20
Textiles	5.1	4	0	0	4.55
Others	12.8	15	0	0	13.9
Total	100	100	100	100	100

Table 6: LandGEM default modelling parameters

Landfill site	k (year^{-1})		L_o (m^3/tonne)	
	CAA	Inventory	CAA	Inventory
Conventional/Sanitary	0.05	0.04	170	100
Arid Area	0.02	0.02	170	100
Wet (Bioreactor)	---	0.70	----	96

Source [12]

This is similar to k value of 0.235 yr^{-1}obtained for India landfill due to the high percentage of food waste recorded in their waste stream [27]. In other studies, k values reported varied from 0.04-0.09 yr^{-1} for US landfills [3], 0.023-0.056 yr^{-1}for Canadian landfills [7] and 0.0429 yr^{-1} for Mexico landfills [28].
Applying the model parameters of L_o = 76.36 m^3/tonne and k = 0.24 yr^{-1} for the landfill sites, CH_4 emissions estimated increased from 831,957 m^3/yr in 1993 until it attained maximum value of 17,179, 275 m^3/yr in 2018. The total CH_4 emissions generated from 1992-2020 was 219,886,140 m^3/yr (Figure 2).

3.3 Model validation
The model validation was done by comparing the output of the new model with the LandGEM model. There are two sets of modeling parameters proposed in LandGEM for different types of landfills; sanitary, Arid and Bioreactor landfills. (Table 6): LandGEM Clean Air Act (CAA) and inventory modeling parameters for sanitary landfills was used.
The maximum CH_4 generation estimated from LandGEM CAA and LandGEM inventory for Olushosun landfill are 63,530,000 m^3/yr and 32,080,000 m^3/yr respectively. This occurred in 2018 at the of landfill's closure. This values are higher than the maximum CH_4 generation value (17,179, 275 m^3/yr) obtained from the new model. The major difference between the models is the calculation steps adopted for the methane gas generating potential (L_o) and first order decay rate**.** The LandGEM model uses constant values for the L_o and k while the new model takes into account the site specific waste composition and landfill site conditions in its estimation.

4. CONCLUSION
The new LFG model developed was based on the widely accepted FOD reaction and the IPCC guidelines for the estimation of methane emissions. Methane generation potential (L_o) was estimated based on actual waste composition, degradable organic carbon (*DOC*) and landfill site characteristics. The methane generation rate (k) was calculated based on the decay rate of each individual waste component. Olushosun landfill was modelled with the new model and LandGEM model and the results were compared. Results revealed maximum CH_4 emissions estimated occurred at the end of landfill's closure.

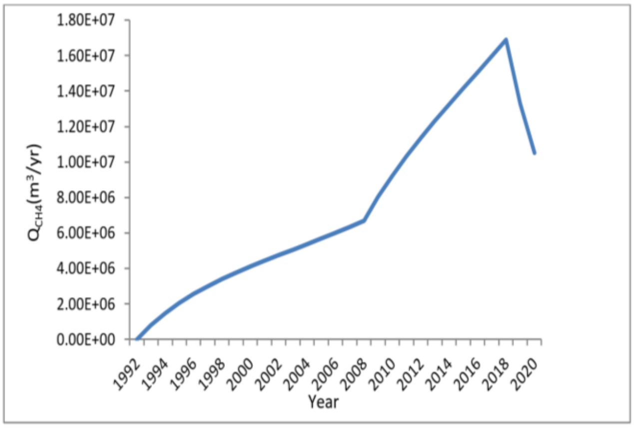

Figure 2: Methane generation in Olushosun landfill

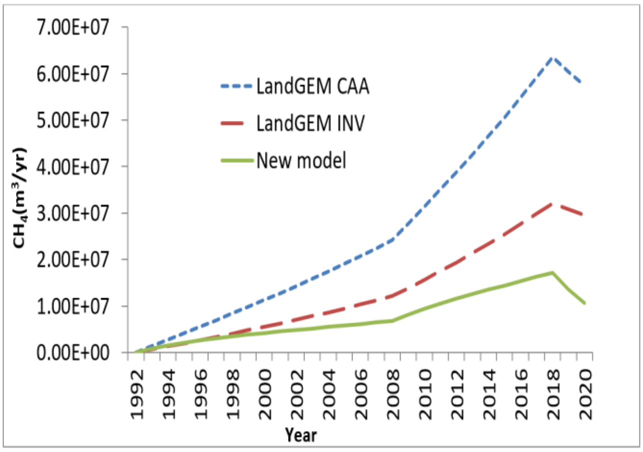

Figure 3: Methane generation in Olushosun landfill with LandGEM and the new model

Methane generation potential (L_o) and methane generation rate (k) parameters were dependent on waste composition and site conditions.Validation of the new model with LandGEM CAA and inventory model parameters showed similar output graph but with significant changes in methane generation. The new model is recommended for use by decision makers and landfill owners as it is simple to use and accommodates varying k and L_o during the landfill operations.

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