

Modelling of landfill gas generation: a review

Alireza Majdinasab · Zhenying Zhang · Qiuyan Yuan

Published online: 12 April 2017
© Springer Science+Business Media Dordrecht 2017

Abstract Landfill gas generation models apply utilizes several different parameters to project Methane (CH₄) generation from a specific mass of disposed waste over a time period in a landfill site. These models are used for better estimating the size of landfill gas (LFG) collection systems, monitoring objectives, assessments, and prognostications. Compared to other options to estimate and control LFG production (such as the application of the test wells), models offer advantages due to the relatively prompt results and cost-effectiveness. Over the recent years, developing LFG generation models has become precedence for the LFG industry. The main trouble in designing and operating an LFG collection system is the uncertainty of LFG generation rates. The LFG generation rates are presently measured via models associated with the waste disposal history, moisture content, gas collection systems, and cover type, which have significant uncertainties. From literature studies, there is not sufficient data regarding the comparison between different models or calibrating them with CH₄-filled landfill data and the CH₄ generation and recovery models are not adequately progressive. The purpose of this study is to provide a comprehensive review of the commonly used models that predict LFG generated in landfill sites as well as discuss their specific characteristics. As a result, these numerical

models are categorized in mathematical, numerical, and zero-, first-, and second-order decay models. Since first-order decay models are extensively used throughout the world, their consideration as multiphase models to make more appropriate projections is discussed in more detail.

Keywords Mathematical modelling · Methane emissions · Zero order · First order · Gas generation rate · Empirical models

1 Introduction

The landfill gas (LFG) is produced from a series of chemical and biological reactions that typically occur in the mass of a disposed waste through landfills. An LFG is generally composed of methane (CH₄) (50–60%), carbon dioxide (CO₂) (40–50%), nitrogen, water vapor, and other innumerable trace gases (Sabour et al. 2007). CH₄ and CO₂ are two of the foremost greenhouse gases (GHG), which makes the study of LFG generations very vital since their accumulation in the atmosphere may result in extreme climate change. CO₂, CH₄, ozone (O₃), vapor, and nitrous oxide (N₂O) are considered as the major compounds found in the atmosphere causing greenhouse effect (US EPA 2016). According to the US EPA (2016), the CH₄ accumulation in the atmosphere has doubled over the last two centuries and this trend

A. Majdinasab (✉) · Z. Zhang · Q. Yuan
University of Manitoba, Winnipeg, MB, Canada
e-mail: majdinaa@myumanitoba.ca

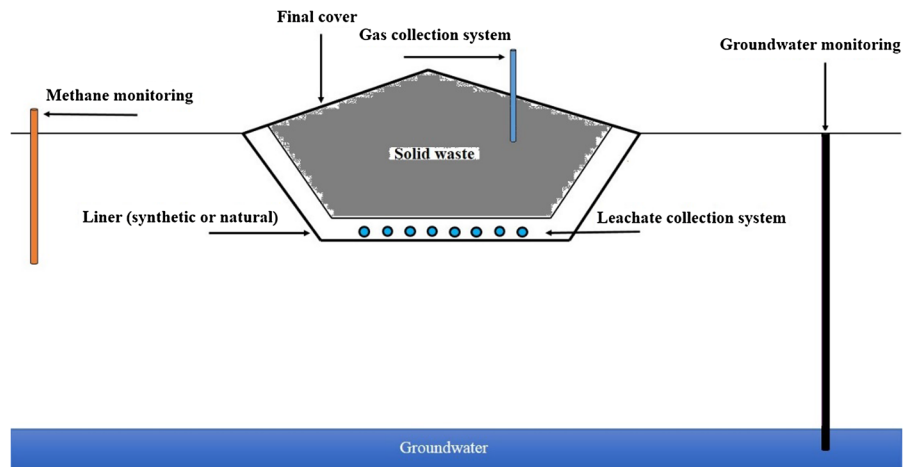


Fig. 1 Different sections of a landfill site

keeps rising, although the rate of increase is decelerating. Over a 100-year time period, CH_4 has the global warming potential 21 times greater than CO_2 by mass (Cohen 2016). Sanitary landfilling is a common method of waste disposal. Figure 1 illustrates a landfill site including biogas collection systems, leachate collections and monitoring equipment. Landfill is considered a major anthropogenic CH_4 generation source, which contributes to the accumulation of CH_4 in the atmosphere (Kamalan 2009). Based on this alarming concern, several regulatory principles have been recently released to estimate and/or manage LFG including Transfer Registers (also called Kiev Protocol or PRTRs) and the Protocol on Pollutants Release (Scharff and Jacobs 2006). Additionally, CH_4 is widely recognized for its significant capacity as a source of energy. In order to use it as an energy source, especially in a large-scale generation, it is important to estimate its production in both quantity and quality (Sabour and Kamalan 2006). According to the literature, several studies have recently implemented modelling approaches to estimate the energy recovery potential of the generated LFG with the consideration of modelling uncertainties (Amini and Reinhart 2011).

All the aforementioned issues have paved the way for the development of various models to provide a better estimation of CH_4 generation in landfill sites. A majority of these models have been developed according to Monod equation and first order decay, such as Gassim, TNO, Afvalzorg, EPER, LandGEM, IPCC, and LFGEEN (Donovan et al. 2010; Ishii and Furuichi 2013; Krause et al. 2016; Penteadó et al.

2012; Kumar et al. 2016; Kamalan 2016). Other models are defined based on Monod equation and zero order decay, such as EPER developed in France. A few models are based on the sequential biological growth to estimate CH_4 emissions such as Halvadakis model (Nastev 1998). Furthermore, some newly developed numerical models utilize neural network and weighted residual methods (Ozakaya et al. 2006; Shariatmadari et al. 2007). The main objective of this study is to offer a comprehensive review on all of these models coupled with their advantages and disadvantages to provide a guideline for researchers, scientists, and policy makers.

2 Landfill gas modelling

In order to recover LFG, the first and foremost stage is to come up with an appropriate estimation of gas generation within the landfill sites. To obtain this goal, numerous LFG generation models have implemented distinct approaches. Nevertheless, the ultimate aim of the LFG modelling is to offer the maximum accuracy for estimating LFG generation. Generally, the modelling of LFG generation could be accomplished using zero order, first order, second order, and/or multi-phase generation models. According to the data released in the previous studies, zero-order model results are not trustworthy due to relatively high levels of inaccuracy (Scharff and Jacobs 2006). When model outcomes are compared to the actual measurement data, higher order models indicate lower inaccuracies

(Oonk et al. 1994) because replacing the first order with a second order or a multi-phase model makes the modelling process much more complicated; therefore, most users prefer using a first order model.

Although several mathematical and numerical models have been developed according to different approaches over the recent years, these models are not readily used since they are available only to the developers. The necessary parameters in these models are often unreliable and they adversely affect the accuracy of the model. Since mathematical and numerical models are complex, several simplified empirical models have also been developed. Although these models are based on the mathematical and numerical models, some processes have been modified to augment simplicity. In fact, the numerical models are not as accurate as the simplified models due to the uncertainty in the influential parameters that reduces the reliability of the numerical models. Some of these models are integrated with special computer software programs to make them more user-friendly. These include the IPCC, the E-PLUS, the French ADEME models, the Dutch Multiphase (AMPM), and the US EPA LandGEM model. Table 1 shows several widely used empirical models as well as their main parameters and their orders.

For example, the US EPA LandGEM model estimates emission rates for CH₄, non-CH₄ organic compounds (NMOCs), CO₂, and other toxic air pollutants from landfill sites (Pierce et al. 2005). The Triangular model assumes that the waste decomposition occurs in two phases, while the E-PLUS model, also developed by the US EPA, estimates the benefits and costs of the LFG collection projects as well as predicts CH₄ flow, NMOCs emissions, and LFG flow (Pierce et al. 2005). The preliminary step of gas generation begins after the first year of deposition, followed by a linear increase from zero in the first year to a maximum amount in the sixth year. After 16 years of deposition, the rate linearly declines to zero (Mor et al. 2006). The ENCON model provides the users with the possibility of inputting specific waste environmental conditions associated with temperature, specific moisture input for individual refuse streams, the overall moisture conditions, and estimates the extraction efficacy (EMCON Associates 1980). According to Table 1, a majority of the presented empirical models are based on the first-order modeling. Landfill evaluators, designers, and operators have broadly used the Intergovernmental Panel on Climate Change (IPCC) and LFG generation models developed by the US EPA. Although the aforementioned

Table 1 Recently developed empirical LFG generation models (Faour 2003; Machado et al. 2009; Thompson et al. 2009)

Model	Main parameters	Order	References
GasSim	Degradation rate constant (k) and waste input carbon content	First-order multiphase model	Gregory et al. (2003)
Triangular model	Methane generation potential (L_0) and peak rate of methane generation	Zero-order model	Tchobanoglous et al. (1993)
Palos Verdes model	Methane generation potential of organic component (L_{0j}) and methane generation potential of the whole waste (L_0)	First-order model with two-phase generation	US EPA (2016)
IPCC model	Methane generation rate constant (k) and Decomposable degradable organic carbon ($DDOC_m$)	First-order model	IPCC (2006)
AMPM	Disposed waste type	First-order multiphase model	Fredenslund et al. (2007)
Scholl Canyon model	Gas generation rate constant for submass (k) and volume of methane remaining to be generated (G)	First-order model	EMCON Associates (1980)
ADEME	Degradation rate fraction (k) and Methane generation potential (FE)	First order model	French Agency for the Environment and Energy Management
GASSFILL	Peak methane generation rate (Q_p) and Methane generation rate (Q)	Two-phase model	Findikakis et al. (1988)

models have small distinctions, the main parameters are defined similarly in all these models.

Several researchers have previously investigated the accuracy of the LFG models to estimate gas generation rate from the landfill sites. For instance, Thompson et al. (2009) investigated 35 landfills in Canada equipped with LFG collection systems, considering only those with adequate waste data and removing outliers. To study the precision of the model outcomes compared to the actual data collected from LFG records, they applied five different LFG generation models to all 35 landfills. Having considered the inefficiency in collecting data, a 20% loss factor was also applied in their studies. The five generation models such as the TNO model, the Scholl Canyon model, the zero-order German EPER model, the LandGEM version 2.01 model, and the Belgium model. The TNO and the German EPER models overvalued the LFG production rate by two- to six-fold. The LandGEM version 2.01, the Belgium were used, and the Scholl Canyon models also showed a standard error of less than 100%. According to that study, only LandGEM version 2.01 model underestimated the LFG generation, while the other four models overestimated the gas generation.

In another study, Willumsen and Terraza (2007) studied LFG generated from six landfills in Europe and South America. The main objective of their research was to provide a comparison between the gas generation rates estimated via various models as compared to the collected data. Results demonstrated that the data values from the Dutch Multiphase First-order Model, the IPCC First-order Model, and the US EPA LandGEM Model were underestimated by 14, 44, and 15%, respectively. Other models such as the Scholl Canyon First-order Model, the Rettenberger First-order Model, and the E-PLUS Model provided outcomes that were considerably different (up to 100%) from the actual data.

The LFG generation models have paved the way for predicting gas generation and recovery according to the operational parameters and waste disposal history. The precision in modelling is necessary to use the outcomes to expand the existing systems, design new ones, and/or evaluate active gas recovery systems. However, the estimation of several parameters that influence the LFG generation is the main challenge in modelling. In the next sections, several major factors affecting the LFG generation are briefly discussed.

2.1 Amount of waste and its composition

The waste composition typically affects both LFG generation capacity and the lag time prior to the gas generation (Karanjekar et al. 2015). As a result, disposed waste could be classified based on inertness and degradability (high, moderate, and poor) of the material. For instance, food waste is a highly degradable and favorable material for generating more gas compared to refuses that contain non- or poorly-degradable substances such as wood, paper, and plastics.

The disposed waste amount can also directly affect the LFG generation. The high amount of refuse being disposed can result in the high availability of resources for gas generation.

2.2 Time

The time is an important factor due to two concerning aspects: the lag time prior to the beginning of gas generation and the overall period of LFG generation (Barlaz et al. 2009). These two factors can have dire consequences on the conceptual design of a landfill. Monitoring the lag time and gas generation period enables the operators to predict the precise time to start the gas collection systems and maintain stable and satisfactory collection efficiency.

2.3 Moisture content

Higher moisture content can increase the rate of gas generation up to a specific optimum point (Bilgili et al. 2007). Based on the climatic conditions and waste composition, the moisture content could be highly variable. Higher moisture contents could result in a faster gas generation in landfills (bioreactor landfills), making it possible to collect LFG in a shorter time interval. Over the recent years, the importance of this parameter has increased as many landfill sites have collected the leachate and recycled it into the landfills. Based on the previous studies, this will cause a considerable acceleration in gas generation (Reinhart and Al-Yousfi 1996; Bergin et al. 2005). The main reason for this acceleration is that the gas generation reaches its peak faster and generates the LFG over a shorter time interval. In terms of the biological aspects, this leachate recirculation provides the anaerobic bacteria with the appropriate moisture content

required for degrading waste and consequently producing LFG. Corti et al. (2007) reported that employing the aforementioned action resulted in generation of 95% of the entire LFG in a landfill 10 years sooner as compared to a conventional landfill. Some studies have also reported the optimum values for the moisture content and leachate recirculation rate. Mehta et al. (2002) conducted a side-by-side comparison of two 8000 metric ton test cells to assess the effect of leachate recirculation on the waste decomposition. They investigated various moisture content values including 14.6, 19.2, 31.7, 34.8 and 38.8%. The optimum moisture content was reported as 38.8% since the maximum decay rate occurred at this level of moisture content. In another study, Sponza and Ağdağ (2004) investigated the influence of leachate recirculation and its rate on the anaerobic degradation of the MSW in three simulated landfill bioreactors. A single pass reactor was operated without leachate injection, while the other two were operated under leachate recirculation rates of 9 and 21 L/day. The leachate recirculation rate of 9 L/day was found to be optimum since it accelerated the MSW mixture stabilization in simulated anaerobic bioreactors.

2.4 Temperature

Generally, microbial activities are influenced by the changes in temperature. An approximation states that each 10 °C increase in the temperature doubles the microbial activity (Pierce et al. 2005). However, this trend is valid only in the optimal range between 30 and 40 °C. The increase in temperature henceforth results in a decline in the microbial activity (Gebert et al. 2003).

Overall, the empirical models combine all of the aforementioned factors into derivative parameters such as the gas generation rate constant (k) and the gas generation potential (L_0), which are widely used in first-order models.

3 LFG modelling parameters

The CH_4 generation potential (L_0) indicates the capacity of a waste stream to produce a specific volume of CH_4 per unit mass; consequently, it is considered as a function of the disposed waste composition. The gas generation rate constant (k) is

a parameter that represents the CH_4 generation time span of a waste stream under certain site specific conditions including waste depth, waste moisture content, oxidation potential, temperature, pH, alkalinity, waste particle size, and density (Garg et al. 2006; Machado et al. 2009). For instance, in a landfill with deeper waste cells, the moisture is better retained at the bottom layers, which accelerates the LFG generation thereby resulting in a shorter time period (Garg et al. 2006). Another hypothesis is that in landfills with higher depth, the insulation improves and the temperature increases, which also accelerates the CH_4 generation rate (Huitric and Rosales 2005). Considering the uncertainties with each of the influential factors, it is imperative and the most challenging part of the modelling to select an appropriate value for k and L_0 .

The gas generation potential may be too variable since the waste stream composition is continuously changing over the lifetime of a landfill site due to the community lifestyle changes or expanding recycling plans (Machado et al. 2009). Additionally, each component in the refuse stream also influences CH_4 generation potential. Waste disposed in landfills is typically composed of lignins, cellulose, hemicelluloses, and proteins that are recognized as the major organic components, which are converted to CH_4 through chemical, physical, and biological processes (Barlaz et al. 1989, 1997). Lignins and cellulose show a considerably variable trend in their rate of degradation under various landfill conditions. For instance, lignins are regarded as recalcitrant compounds under anaerobic conditions. Besides, pH and temperature could also have a significant impact on the microbial activities in the waste disposed in the landfills (McBean et al. 1995). The influence of all the aforementioned components has resulted in quantification of L_0 under different conditions by adjusting the waste quantity using a biodegradation factor. Table 2 represents the values of the biodegradation factor for different waste materials suggested by previous researchers. In addition, moisture content regulates CH_4 generation through microbial activities by providing better conditions for the microorganisms to propagate (Barlaz et al. 1990).

The appropriate values for k and L_0 could be determined via collected LFG data, theoretical predictions, or laboratory experiments. According to Machado et al. (2009), the major challenge in

Table 2 Different biodegradable fraction values recommended by previous researchers (Machado et al. 2009)

Biodegradable fraction						References
Wood	Food waste	Paper	Textiles	Cardboard	Garden waste	
0.30–0.33		0.30–0.40	0.17–0.25	0.44	0.20–0.51	Harries et al. (2001)
0.17	0.64	0.40	0.32	0.41	0.35	Lobo (2003)
0.14	0.70	0.19–0.56		0.39	0.70–0.34	Barlaz et al. (1997)
0.61	0.58	0.44	0.40	0.38	0.45	Tchobanoglous et al. (1993), Bonori et al. (2001)

predicting the values through laboratory experiments is to simulate the actual conditions of an LFG site at lab-scale. In addition, theoretical predictions come up with maximum values for L_0 , which are never reached during an experiment. Machado et al. (2009) assumed the main reason for this issue is that not all parts of the organic refuse are biodegradable and thus, the application of biodegradability factor is not applicable for all components. In order to predict LFG generation, most simplified models follow Eq. (1) but with different k and L_0 values.

$$Q_g = \beta k M L_0 e^{-k} \quad (1)$$

where Q_g is the annual LFG generation ($\text{m}^3 \text{ year}^{-1}$), β is the inverse ratio of the fraction of CH_4 content, M is the average annual solid waste acceptance mass (Mg), t is the age of disposed waste (year), L_0 is the CH_4 generation potential ($\text{m}^3 \text{ Mg}^{-1}$), and k is the LFG generation rate constant (year^{-1}).

Several organizations including IPCC and US EPA have suggested default values for k and L_0 . For instance, k values according to the literature typically range from 0.01 to 0.21 year^{-1} with 0.04 year^{-1} considered as the most commonly used value (Pierce et al. 2005; Garg et al. 2006). However, other values such as 0.3 and 0.5 year^{-1} have also been mentioned under certain situations such as the rapidly degradable portions of waste and bioreactor landfills (Faour et al. 2007; Ogor and Guerbois 2005).

The US EPA has suggested the value of 0.3 year^{-1} for wet landfills, 0.02 year^{-1} for landfills receiving less than 63.5 cm (25 inches) of rainfall per year and 0.04 year^{-1} for those receiving over 63.5 cm (25 inches) of rainfall per year (US EPA 2016). Although the US EPA recommended values that provided the best fit based on 40 different landfills, the estimated CH_4 generation still has a deviation from 30 to 400% from actual measurements (US EPA 2016). Machado et al. (2009) have reported that high k values of about

0.2 year^{-1} are related to high moisture and higher portions of rapidly biodegradable refuse. They discussed that the high moisture and portions of rapidly biodegradable refuse are due to the presence of high food waste with their respective values of 0.26 kg water/dry-kg and 0.70. Table 3 represents various k values as suggested by IPCC.

Similarly, the values suggested for L_0 also vary depending on the parameters. Different studies have revealed a range of L_0 values from 6 to $270 \text{ m}^3 \text{ Mg}^{-1}$ based on different case studies (US EPA 2016). The US EPA has recommended the L_0 value of $100 \text{ m}^3 \text{ Mg}^{-1}$ for “as received waste”. Machado et al. (2009) used an L_0 value of $70 \text{ m}^3 \text{ Mg}^{-1}$ for tropical landfilling situations for on-site and lab-scale measurements. Bentley et al. (2005) calculated both k and L_0 values for seven case studies involving landfills via the application of baro-pneumatic measurements, which are presented in Table 4. The average values for L_0 and k calculated in that study were $107 \text{ m}^3 \text{ Mg}^{-1}$ and 0.153 year^{-1} , respectively. Another study by Budka et al. (2007) also reported different values of L_0 , which are represented in Table 5.

Bentley et al. (2005) have also proposed a new method of using barometric pressure data to calculate derivative parameters of LFG generation rate. This method is based on estimating the LFG generation via measuring pressure responses under the landfill cover in comparison with the atmospheric pressure changes. In this method, pressure changes are regulated under and above the landfill cover through the application of sensors installed at different depths and areas for several consecutive days. The data released in this study indicated that the barometric pressure in the deeper zones of the landfill cells was higher than the atmospheric pressure and this increase continued with the depth. Bentley et al. (2005) also reported that the inside landfill pressure ranged from approximately the atmospheric pressure (163 mm H_2O) to 8.6 atm

Table 3 Different k values (year⁻¹) recommended by IPCC (Machado et al. 2009)

Waste type\weather		Dry tropical weather		Wet tropical weather		Dry northern and temperate weather		Wet northern and temperate weather	
		Range	Default	Range	Default	Range	Default	Range	Default
Bulk waste	Discarded furniture, large appliances	0.05–0.08	0.065	0.15–0.20	0.170	0.04–0.06	0.05	0.08–0.10	0.09
Rapidly degradable waste	Sewage sludge, food refuse	0.07–0.10	0.085	0.17–0.70	0.400	0.05–0.08	0.06	0.10–0.20	0.185
Moderately degradable waste	Park and garden waste, other organic Putrescible (non-food)	0.05–0.08	0.065	0.15–0.20	0.170	0.04–0.06	0.05	0.06–0.10	0.10
Slowly degradable waste	Straw and wood waste	0.02–0.04	0.025	0.03–0.05	0.035	0.01–0.03	0.02	0.02–0.04	0.03
	Textiles and paper wastes	0.04–0.06	0.045	0.06–0.085	0.70	0.03–0.05	0.04	0.05–0.07	0.06

Table 4 Different L₀ and k values as well as other landfills conditions reported by Bentley et al. (2005)

Landfill name	k (year ⁻¹)	L ₀ (m ³ Mg ⁻¹)	CH ₄ gas fraction	LFG flow Q (Baro-pneumatic) (ft ³ /min)	LFG flow Q (Calibrated first order decay model) (ft ³ /min)	Time since closure (yearr)	Waste (tons) (at the time of the analysis)
Houser’e Mill Road, GA	0.148	102	0.5	510	510	12	7.26E + 05
St. Landry Parish, LA	0.237	104	0.56	785	757	active	1.06E + 06
Louisiana	0.238	110	0.506	7098	7028	active	3.74E + 06
Georgia	0.086	108	0.56	142	146	10	4.75E + 05
N. Shelby Memphis TN	0.078	103	0.5	1969	1969	10	7.76E + 06
Decatur County, GA	0.179	115	0.5	551	551	0–6	9.73E + 05
St Landry parish, GA	0.104	112	0.56	785	784	active	1.06E + 06

Table 5 Different L₀ outcomes reported by Budka et al. (2007)

Type of landfill	L ₀ (m ³ Mg ⁻¹)		
	Slowly degrading	Moderately degrading	Readily degrading
Bioreactor	38	77	35
Conventional	30	84	42

(1400 mm H₂O). They mentioned two main benefits from their method. Firstly, the interpretation of the data was possible via a quantitative gas flow equation based on Darcy’s law and continuity equations. Secondly, the data obtained from the pressure response is imposed over a huge area which reduces the necessity to interpolate between spatial zones to provide accurate gas generation estimation.

In another study, Garg et al. (2006) developed a model to calculate the k value via the application of a fuzzy synthetic evaluation method. They provided a comparison between their calculated k value outcomes and the values calculated in 32 different studies, or estimated by LandGEM model using EPA’s 2E method for different case studies. The average k value was an overestimation of the given value by 79% with

a regression coefficient of 0.79, the fuzzy-based model outcomes ranged from 43 (underestimated) to 287% (overestimated) of the values calculated in those studies. They also conducted a sensitivity analysis associated with k values and confirmed that these values were more sensitive to the depth of the landfill and biodegradable organic fraction of the waste than mean temperature and precipitation.

Tolaymat et al. (2010) have also evaluated the site-specific values for k and L_0 for the MSW landfills operated as bioreactors. To improve the LFG predictability, LFG flow rates and composition were monitored for a 4-year period using one conventional and two bioreactor landfill cells in a landfill located in Louisville, KY. The reported site-specific value for L_0 was approximately $48.4 \text{ m}^3 \text{ Mg}^{-1}$. The estimated k values for the conventional cell was 0.06 year^{-1} , while the average value for the two bioreactor cells was 0.11 year^{-1} which was much higher.

4 Available models

There are generally three approaches to mathematically present LFG generation rate: (1) estimation as a summation of mathematical functions indicating the individual kinetics of the contemplated physico-chemical processes taking place during the waste anaerobic degradation, (2) estimation as a simple empirical function or as a mixture of simple functions of a general kinetic factor, and (3) numerical models that elucidate gas generation via digits.

Some models deal with a general kinetic parameter, which is the most prevalent kind of model available in the literature (Findikakis and Leckie 1979; Van Heut 1986; Gardner and Probert 1993; Hartz 1982). The overall kinetic parameter is empirically adjusted to the observed production rates for data comparison. It is simply assumed as a start-up period through which little or no CH_4 is generated, followed by active CH_4 generation period mostly demonstrated by exponential or linear relationships, or their combinations. The summation of the gas generation rates would result in obtaining the cumulative gas generation over the active generation period and can be associated with the assumed preliminary generation capacity of the landfill.

Derivation of most of these relatively simple models is defined via a theoretical approach, which

is based on the general kinetic expression for the biodegradation processes commonly known as Monod's equation as follows:

$$\frac{dC}{dt} = \frac{KCx}{K_c + C} \quad (2)$$

where C is the concentration of remaining substrate at time t (kg of the waste degradable organic fraction per m^3 of the waste), such as organic material, x is the microorganisms' concentration (kg of the biomass per m^3 of the waste), K_c is a waste concentration through which the rate is one-half of the maximum digestion of substrate, and K is the maximum substrate utilization per unit mass of microorganisms. There are two extreme functions through which the Monod's equation could be approximated depending on the concentration of the substrate: zero-order reaction and first-order reaction. For the zero-order reaction, if the concentration of the microorganisms (x) remains constant, the rate of substrate consumption (dC/dt) also remains constant. For the first-order reaction, if the concentration of the microorganisms (x) remains constant, the rate of substrate utilization could be considered as a linear function of the substrate's concentration.

4.1 Zero-order model

In this type of model, the biogas generation rate produced in landfill sites remains steady with the change in time. As a result, the type and age of the waste have no effects on the gas generation. The following subsections elucidate some zero-order models that are readily used by researchers.

4.1.1 IPCC

This model provides a zero-order kinetic reaction based on the degradable material within the waste, population, and CH_4 correction factor as indicated in Eq. (3) (IPCC 1996):

$$E_{\text{CH}_4} = (\text{MSWT} \times \text{MSWF} \times \text{MCF} \times \text{DOC} \times \text{DOCF} \times 16/12 - R) \times (1 - \text{OX}) \quad (3)$$

where E_{CH_4} is CH_4 emissions from landfills, MSWT is the total municipal solid waste (MSW), MSWF is a fraction of MSW in a landfill, MCF is the CH_4 correction factor (fraction) (IPCC default value is 0.6),

DOC is the degradable organic carbon which is recommended to be 15% w/w as the default value by the IPCC, DOCF is the fraction of actually decomposed DOC in the waste which is recommended to be 77% w/w by the IPCC, F is the fraction of the CH₄ in the LFG (the IPCC default is 0.5 v/v), 16/12 is the conversion factor from C to CH₄, R is the recovered CH₄, and OX is the oxidation factor (fraction, IPCC default is 0). Table 6 represents different default values for MCF in IPCC model based on the site type and Table 7 represents values for DOC parameter in the IPCC model for different types of waste.

The way to calculate the MSWT is to multiply the population by the annual MSW generation rate per capita, which is available for different countries and regions. These distinctions could play a key role in the estimation of the resulting emissions, as every waste stream is likely to have a different DOC content and subsequently CH₄ production capacity. Generally, countries should include three types of waste streams for the estimation of MSWT generated: commercial or market waste, garden and yard waste, and household waste.

4.1.2 SWANA zero order

A zero-order model has been developed by Solid Waste Association of North America (SWANA) which considers different kinds of waste. This model formula is represented by Eq. (4) (SWANA 1998):

$$Q = \frac{ML_0}{(t_0 - t_f)} \tag{4}$$

where Q is the rate of CH₄ generation, M is the mass of waste disposed in the landfill, L₀ is the potential of CH₄ generation per mass of the waste, t₀ and t_f are the lag time and time until CH₄ is generated, respectively.

Table 6 Different MCF default values for the IPCC model (IPCC 2006)

Type of site	Default values for MCF
Unmanaged-uncategorized solid waste disposal systems (SWDSs)	0.6
Unmanaged shallow (<5 m waste)	0.4
Unmanaged-deep (>5 m waste)	0.8
Managed	1.0

Table 7 Different DOC default values for the IPCC model (IPCC 2006)

Type of waste	Default values for DOC (%) (by weight)
Non-food organic waste	17
Food waste	15
Textiles and papers	40
Wood and straw waste	30

4.1.3 EPER

The EPER model is another zero-order model, which was developed in Germany, and it is represented by Eq. (5):

$$M_e = M \times BDC \times BDC_f \times F \times D \times C \tag{5}$$

where M_e is the amount of CH₄ emission diffused, M is the amount of annual waste in a landfill, BDC is the proportion of biodegradable carbon (the default value is 0.15), BDC_f is the proportion of biodegradable carbon converted to CH₄ (default value is 0.5), F is a calculation factor of carbon converted into CH₄ (the default value is 1.33), D is the efficiency of collection with default values for active LFG recovery and cover, active degassing, and no recovery as 0.1, 0.4, and 0.9, respectively. C is the CH₄ concentration with the default value of 0.5. The outcomes of this model would be the same as a first-order degradation model if the constant amount of waste with the same composition were landfilled.

4.2 First-order model

Most of the worldwide and available models commonly used to estimate the rate of LFG generated in landfills have been developed based on the first-order decay reaction. Generally, the landfill conditions (precipitation, temperature, and climate), waste quantity, and waste quality (waste degradation over time, carbon content, moisture content, and age of waste) have been implicitly considered in these models. In other words, the first-order kinetic model considers the effect of carbon depletion in the waste over time (Ozakaya et al. 2006). The first-order models assume that there is an exponential relationship between the waste carbon and the decay rate with time (Gardner and Probert 1993).

Although the current models focusing on LFG generation are mostly based on first order kinetics (exponential degradation), the long-term emissions of landfills have been typically underestimated in the literature. Tintner et al. (2012) aimed to mitigate this problematic issue by focusing on the quantification and curve fitting of the LFG production throughout the final phase of degradation under optimal anaerobic conditions. To achieve this objective, the mechanically and biologically treated waste materials were examined under long-term LFG generation period from 240 to 1830 days. The observed gas sum curve resulted in greater values compared to the widely used exponential decay models. Here are some of the most commonly used first order kinetic models.

4.2.1 TNO

This model estimates LFG generation according to the waste organic carbon degradation as represented in Eq. (6):

$$\alpha_t = \zeta 1.87 A C_0 k_1 e^{-k_1 t} \quad (6)$$

where α_t is the LFG generation at a given time, ζ is the dissimilation (or catabolism) factor of the organic waste (the default value is 0.58), A is the amount of waste placed in the landfill, C_0 is the waste organic carbon content, and k_1 is the degradation constant with the default value of 0.094. There are seven categories defined for the term C_0 in this model including shredder waste, contaminated soil, compost and sewage sludge, street cleaning waste, construction and demolition waste, coarse household waste, commercial waste with the default values of 130, 11, 90, 11, 130, and 11, respectively.

4.2.2 SWANA first order

In this model, the effect of waste age on the gas generation is incorporated to facilitate the exponential decrease in LFG generation rates for the unit waste amount. The formula for this model is represented in Eq. (7) (SWANA 1998):

$$Q = M L_0 e^{-k t} \quad (7)$$

where Q is the CH_4 generation rate, k is a constant for the first-order degradation and L_0 is the CH_4 generation potential of the waste unit of mass.

4.2.3 LandGEM

A software named LandGEM has been developed by the US EPA, which calculates the LFG generation based on the same formula as MSW. This model estimates the annual gas generation based on the first-order degradation kinetic over a specified period of time (US EPA 2016). This model is represented in Eq. (8).

$$Q_{\text{CH}_4} = \sum k L_0 M_i (e^{-k t}) \quad (8)$$

where Q is the total gas generation rate, n is the number of years for the placement of the waste, and M_i is the mass of solid waste placed in year i . According to the US EPA protocols, the waste composition through this model reflects the composition of the MSW in the US, inert compounds, and other non-hazardous materials. In some cases, when landfills contain inert materials (i.e. non-biodegradable waste), such as ash resulting from waste combustion, this portion is likely to be subtracted from the waste acceptance rates. This model suggests subtracting inert materials when the documentation is provided and permitted by the regulatory authority. This case does not include those landfills containing MSW that may or may not be decomposable. The LandGEM model provides the values for the gas generation rate constant and gas generation potential for both AP42 and CAA standards (Clean Air Act 1963). For standard landfills, it is highly recommended to use AP42 default values. The CAA default value of $180 \text{ m}^3 \text{ CH}_4 \text{ tone}^{-1}$ waste recommends a significant amount of gas generation potential (L_0) (Scharff and Jacobs 2006). LandGEM as a first-order kinetic model contains inputs including the years of waste acceptance, the annual waste acceptance rate or the amount of waste in place, the landfill design capacity, placement of the hazardous waste in the landfill, the potential values for k and L_0 , and the total and individual concentration of the non- CH_4 organic compounds (NMOCs). Default values for k and L_0 may be implemented into the model or site-specific values could be developed through field measurements.

According to Thorneloe et al. (1999), LandGEM outputs are as follows: the individual pollutant emissions, two sets of default values incorporated in the model to calculate emissions (the first set is for

specifying the Federal regulatory requirements known as “Clean Air Act defaults” and the other set is for development of emission inventories known as “AP-42 defaults”), estimation of the landfill closure according to the waste acceptance rate and landfill capacity, estimation of the CH₄, NMOCs, and selected air pollutants’ emission rates on an annual basis over the active lifespan of a landfill and for a certain number of years after the landfill is closed, and emission graphs for individual pollutant.

LandGEM has gained high attention in the literature as a reliable model to predict LFG generation, especially over the recent years. In one study, Amini et al. (2012) evaluated four methods to quantify first-order model parameters (L₀ and k) using LandGEM model. The results obtained from five case study landfills in Florida showed that L₀ ranged between 56 and 77 m³ Mg⁻¹ and k ranged from 0.04 to 0.13 year⁻¹ for conventional landfills while the value of 0.10 year⁻¹ was obtained for wet cells. They also reported that the model outcomes for LFG generation rate were on average less than the actual values collected.

4.2.4 Afvalzorg

This type of first-order kinetic multiphase model has the capability of estimating LFG generation based on eight waste categories and three fractions. Each fraction is separately taken into account to estimate LFG generation. For some categories of waste, no carbon content or organic matter data were provided (Scharff and Jacobs 2006). The amount of organic matter content for eight waste categories used in the

Afvalzorg model are shown in Table 8. Equation (9) represents the mathematical format of this model.

$$\alpha_t = \zeta \sum_{(i=1)}^3 1.87AC_{0,i}k_{1,i}e^{-k_{1,i}t} \tag{9}$$

where α_t is the LFG generation at time t, ζ is the dissimilation factor, i is the waste fraction corresponded with $k_{1,i}$ degradation rate constant, which ranges between 0.03 and 0.231, and A is the amount of waste, and $C_{0,i}$ is the primary concentration of the waste fraction i.

4.2.5 GasSim

The GasSim model is another first-order kinetic multiphase model, which was developed by Scheepers and van Zantan (1994). According to the manual Version 2.0 (Golder Associates 2006), there is no complete set of equations applicable to the GasSim model. Thus, in the study done by Scheepers and van Zantan (1994), it was impossible to reproduce the equations for this model, since the calculation modules in this software are secure. This model’s requirements are specific to the year of disposal and waste input is in Mg. Different categories of waste and their carbon content typically used in GasSim model are represented in Table 9. The degradability of the three waste fractions and different k values used in GasSim are represented in Table 10 (Scharff and Jacobs 2006).

4.2.6 EPER France

The EPER France model provides the estimation of CH₄ emissions for landfill sites whether it is joined or

Table 8 Organic matter content for waste categories used in the Afvalzorg model

Category of waste	Minimum content of organic matter (kg Mg ⁻¹)				Minimum content of organic matter (kg Mg ⁻¹)			
	Total	Slow	Moderate	Rapid	Total	Slow	Moderate	Rapid
Commercial waste	260	104	52	13	270	108	54	19
Shredder waste	60	18	6	0	70	25	11	0
Sewage sludge and compost	150	45	38	8	160	48	45	11
Household waste	300	45	75	60	320	48	90	70
Contaminated soil	40	6	2	0	42	8	3	0
Construction and demolition	44	12	6	0	46	16	8	0
Street cleansing waste	90	27	18	9	100	40	22	12
Coarse household waste	260	104	39	13	270	108	49	19

Table 9 Categories of waste as well as their carbon content used in the GasSim model

Categories of waste	Carbon content (kg ^c Mg ⁻¹)
Chemical sludge	0
Sewage sludge	36
Liquid inert	0
Composted organic material	51
Waste sorted at MRF	0
Inert	0
Commercial waste	182
Incinerator ash	4
Recycling schemes	0
Civic amenity	71
Domestic	118
Industrial liquid waste	0
Liquid inert	0

not joined to an LFG collection system via a multiphase model called “ADEME” (version 15/12/2002). The formula for this multiphase model is mathematically represented in Eq. (10):

$$FE_{CH_4} = \sum FE_0 \times \left(\sum A_i \times p_i \times k_i \times e^{-k_i t} \right) \quad (10)$$

where, FE_{CH_4} is the annual CH_4 generation rate, FE_0 is the CH_4 generation potential, p is the fraction of waste with degradation constant of k_i , and A_i is the normalization factor.

The left and right sides of the Eq. (10) do not match dimensionally and it seems that the waste amount in $Mg \text{ year}^{-1}$ is absent on the right side of the equation. In the spreadsheet of this model, the amount of waste on an annual basis is utilized in the calculations. The normalization factor is not included in the spreadsheet, whereas it is defined in the equation for the model. This model defines three waste categories and each category has a particular CH_4 generation potential per Mg of waste. Table 11 represents the waste categories

as well as their respective CH_4 generation potential. Table 12 shows the fractions and k values for different waste categories (Scharff and Jacobs 2006).

4.2.7 Mexico

The basic assumption in this model is that there is a 1-year lag between the waste disposed in the cells and LFG production. The model also assumes that an exponential decline occurs in the CH_4 generation rate for each unit of waste after 1 year due to the consumption of the waste organic fraction. The model estimates the LFG generation rate for a landfill in a given year with known (or estimated) year-to-year rate of solid waste disposal according to the equation shown in Eq. (11):

$$Q_M = \sum_{i=1}^n 2kL_0M_i(e^{-kt}) \quad (11)$$

This formula has been published in Title 40 of the US Code of Federal Regulations (CFR) Part 60 (Stege and Murray 2003). In order to estimate the gas generation rate, this model needs site-specific data for all the information required, except for the L_0 and k values. Actually, this model uses default values for L_0 and k that were obtained based on three aspects: the relationship between L_0 and k values; the average precipitation rate measured at US landfills annually, and the specific data collected from representative landfill sites in Mexico (Stege and Murray 2003). These values are represented in Table 13 with an assumption that the LFG composition generated from landfills is about 50% CH_4 and the rest is comprised of other gases such as CO_2 and trace amounts of other components.

4.2.8 LFGGEN

The University of Central Florida developed this model and used it for the first time (Keely 1994).

Table 10 Degradability of the three waste fractions and different k values used in the GasSim model

Degradability	k values (year ⁻¹)		
	Wet	Moderate	Dry
Slow	0.076	0.046	0.013
Moderate	0.116	0.076	0.046
Rapid	0.694	0.116	0.076

Table 11 Categories of waste and CH₄ production potential in the ADEME model

Waste category	Categories of waste in ADEME	CH ₄ production (m ³ Mg ⁻¹)
1	Yard waste, MSW, sludges	100
2	Biologically pretreated waste, industrial waste, commercial waste	50
3	Non-biodegradable waste, inert waste	0

Table 12 Different fractions as well as k values used in ADEME model

Category	Overall k value (year ⁻¹)	Fractions			
		1 (k = 0.040 year ⁻¹) %	2 (k = 0.500 year ⁻¹) %	3 (k = 0.100 year ⁻¹) %	%
1	0.120	30	15	55	
2	0.120	30	15	55	
3	0.000	0	0	0	

Basically, this model estimates LFG generation based on three assumptions: first, methanogenesis process starts after a short period of lag time; second, the first phase of methanogenesis process follows a linearly increasing generation rate; and third, the second phase of methanogenesis process follows a first-order kinetic represented by an exponentially decreasing generation rate. Other features of this model are discussed as follows.

There are 11 categories for the biodegradable solid waste in this model. The methods of analysis include Biochemical CH₄ Potential (BMP), EPA Tire3, biodegradability factors, and theoretical stoichiometric production of CH₄ and CO₂. The solid waste is divided into three categories in terms of moisture content: wet, moderate, and dry. The waste biodegradation is divided into three categories, which include rapid, moderate, and slow (biodegradability rate is also a function of moisture).

This model considers the lag time to establish anaerobic conditions. After this delay, the gas generation rate follows a linear increase to a specific peak rate (Q_s), which occurs at the end of the year (t_p). After the peak is observed, the generation rate follows an exponential decline from the peak to a near-zero value at the end of the biodegradation time (t₉₉). During this time (t₉₉), the gas generation rate falls to approximately one percent of the peak rate. The assumption in this model is that the characteristic times (t₀, t_p, and t₉₉) are dependent on the moisture content and waste type. The specific peak rate (Q_s) is also a function of the CH₄ generation potential according to the Eq. (12) (Reinhart and Faur 2004):

$$Q_s = L_0 [2k / (k(t_p - t_0) + 2)] \tag{12}$$

The biodegradation constant k for the second phase of methanogenesis is related to the assumed times as represented in Eq. (13):

Table 13 Different L₀ and k values used in the Mexico model

k (year ⁻¹)	Annual precipitation (mm year ⁻¹)	L ₀ (m ³ Mg ⁻¹)	Annual precipitation (mm year ⁻¹)
0.040	0–249	60	0–249
0.050	250–499	80	250–499
0.065	500–999	84	At least 500
0.080	At least 1000		

$$k = (-\ln 0.01)/(t_{99} - t_p) \quad (13)$$

4.3 Second-order models

These models explain the complicated reactions that occur during the waste degradation period via several first-order reactions with different kinetic rates. The LFG generation rate could be modelled via the second-order kinetics using a complex set of different reactions (Reinhart and Faur 2004).

4.4 Complex mathematical models

These models explicitly consider some or most of the well-known physical, chemical and biochemical variables affecting the gas generation rate in complex mathematical functions. Some of these important variables include temperature, composition, moisture content, adsorption, absorption, volatilization, evaporation, complications, filtration, dilution, neutralization, oxidation, reduction, and precipitation. Without a detailed characterization of the actual conditions in a landfill, it is not possible to evaluate the gas generation rate with any certainty. This model needs a very detailed analysis and a considerable amount of measurements (Nastev 1998).

For instance, the Halvadakis model developed by El-Fadel et al. (1989) is based on the sequential biological growth and is considered as a representative complex mathematical model used for estimation of LFG generation. A system of first-order equations is used to describe a complicated microbial landfill ecosystem. They were described in terms of pathways and sinks, carbon sources, digestion of the aqueous carbon for the acidogenic and methanogenic biomass growth, which explain the hydrolysis of the biogasifiable and hydrolysable components of waste, acetate utilization, and subsequent generation of CH₄ and CO₂. This is equivalent to a simplified microbial food chain. Nevertheless, this model ignores the amount of CH₄ generated by the CO₂ reduction with hydrogen, which constitutes roughly 25–30% of the total CH₄ generated. This model also considers carbon in seven possible forms based on the mass balance equations as follows: Aqueous carbon is calculated according to Eq. (14):

$$dC_{(aq)}/dt = \sum k_{ha}C_{(s)i} - (1/Y_A) (\mu_A KC_{(aq)}/(K_{sa} - C_{(aq)}))C_{xa} \quad (14)$$

where C(aq) is the aqueous carbon concentration, k_{ha} is the hydrolysis rate of refuse component a, Y_A is the mass of acidogenic biomass carbon formed per mass of substrate dissolved organic carbon metabolized (a dimensionless fraction), μ_A is the acidogenic biomass maximum specific growth rate constant, and K_{sa} is the half saturation constant for acidogens (carbon basis).

Solid carbon is calculated according to Eq. (15):

$$dC_{(s)}/dt = -k_{ha}C_s \quad (15)$$

Carbon in acidogenic biomass is calculated according to Eq. (16):

$$dC_{(xa)}/dt = [(\mu_A C_{(aq)})/(k_{ha} - C_{(aq)}) - k_{da}]C_{xa} \quad (16)$$

where k_{da} is the acidogenic biomass death rate constant. Carbon in methanogenic biomass is calculated according to Eq. (17):

$$dC_{(xm)}/dt = [(\mu_m C_{(Ac)})/(K_{sm} + C_{(Ac)}) - k_{dm}]C_{xm} \quad (17)$$

where μ_m is the methanogenic biomass maximum growth rate, K_{sm} is the half saturation constant for methanogens (carbon basis).

Carbon in acetate is calculated according to Eq. (18):

$$dC_{(Ac)}/dt = Y_{Ac} [((1 - Y_{Ac})/Y_{Ac})\mu_A (C_{(aq)})/(K_{sa} + C_{(aq)}) + k_{da}] - [(1/Y_m)\mu_m (C_{(Ac)})/(K_{sm} - C_{(Ac)})]C_{xm} \quad (18)$$

where Y_{Ac} is the acetate carbon fractional formation yield coefficient, and Y_m is the mass of methanogenic biomass carbon formed per mass of acetate carbon utilized (dimensionless).

Carbon in CO₂ is calculated according to Eq. (19):

$$dC_{(CO_2)}/dt = (1 - Y_{Ac}) [((1 - Y_{Ac})/Y_{Ac})\mu_A (C_{(aq)})/(K_{sa} + C_{(aq)}) + k_{da}]C_{xa} + (1 - Y_{CH_4}) [((1 - Y_m)/Y_m)\mu_m (C_{(Ac)})/(K_{sm} + C_{(Ac)}) + k_{dm}]C_{xm} (1 - Y_{CH_4}) [((1 - Y_m)/Y_m)\mu_m (C_{(Ac)})/(K_{sm} + C_{(Ac)}) + k_{dm}]C_{xm} \quad (19)$$

where Y_{CH_4} is the CH_4 carbon fractional formation yield coefficient (dimensionless).

Carbon in CH_4 is calculated according to Eq. (20):

$$dC_{(CH_4)}/dt = Y_{CH_4} \left[\left(\frac{(1 - Y_m)}{Y_m} \right) \mu_m \right. \\ \left. \left(\frac{C_{(Ac)}}{(K_{sm} + C_{(Ac)})} \right) + k_{dm} \right] C_{xm} \tag{20}$$

4.5 Numerical models

Numerical models are strong implements to simulate and model the whole phenomena that occur during the waste degradation and gas generation (Afshar 2002). Therefore, it could be incorporated into a simpler method. In this case, a technique called “Weighted Residual Method (WRM)” has been successfully implemented to promote the simplicity. The application of this method based on the data collected from a real landfill site has confirmed the reliability of numerical models. The formula represented in Eq. (21) could be utilized for every landfill site with a few CH_4 measurements as follows:

$$\iint_{\text{Domain}} Wlp(G - \psi) dt dW \\ = \iint_{\text{Domain}} Amn \left(Wlp \sum Nmn \right) \leftrightarrow f_1 \\ = k_1 \sum Amn \tag{21}$$

where w_{lp} is a weighting function, G is the approximated CH_4 generation, Ψ is a function to comply the boundary condition, N_{mn} is considered as a trail function that is assumed to be zero on the boundaries, k_1 is the coefficient matrices, f_1 is the right hand side matrix which is known and A_{mn} is a coefficient that should be specified and is an unknown matrix. The ultimate goal of WRM is to select Amn in a way that the residue (R) declines over a determined domain. R is the difference between the left and right side of the Eq. (21).

4.6 Comparison of the studied models

In order to provide a comparison between different types of models, Table 14 represents a brief review of all the models discussed in this study as well as their basic assumptions, advantages and disadvantages. According to Table 14, most of the empirical models predict the LFG generation based on the degradable

organic carbon, portion of the degradable carbon, or carbon content of the waste. Some of these models including Afvalzorg and GasSim have classified the waste into different categories. In terms of the ease of operation, some models are more user-friendly compared to others. For instance, Land GEM and Mexico have a user-friendly operation in the datasheet environment, while EPER France model contains a normalization factor that is not considered in the spreadsheet.

In order to estimate the LFG generation, several studies have recently investigated different models in terms of their application for various objectives. For instance, Cakir et al. (2016) have used three different methodologies and one approach to investigate the LFG potential as an energy source to produce heat and electricity recovered from the MSW. The methods they used include Afvalzorg multiphase model, LandGEM, and the IPCC (2006). The LFG generated using the multiphase and the IPCC (2006) models were 291,897,215 and 491,752,247 m^3 , respectively. The LFG generated via the LandGEM model with three k values of 0.35, 0.1 and 0.35 $year^{-1}$ were 792,073,359, 769,734,749 and 681,685,027 m^3 , respectively.

Mahar et al. (2016) provided a new approach to simulate the cumulative LFG generation and its rate for a pretreated MSW landfill using four models. These models include first order exponential model, modified Gompertz model, single component combined growth and decay model, and Gaussian function. They developed a new multi-component model based on the single component combined growth and decay model using an anaerobic landfill reactor acting as a simulator to treat the pretreated MSW. Their results confirmed that in terms of cumulative LFG generation simulation, modified Gompertz model offered better fit as compared to the first- order exponential model. They also reported that newly developed multi-component model (which has been developed based on biochemical processes) was more precise as compared to the single component combined growth and decay model and Gaussian function.

In another study, Chakma and Mathur (2016) developed a new method to predict the optimum generation of long-term spatial-temporal landfill gas components on post closure landfill. The model used in this study was a first order kinetic model that incorporated the chemical and biological processes

Table 14 An overview of the discussed models, their assumptions, advantages, and disadvantages

Model name	Formula	Assumptions	Advantages	Disadvantages
IPCC	$Q = (MSWT \times MSWF \times MCF \times DOC \times DOCF \times 16/12 - R) \times (1 - OX)$	Zero order; based on degradable organic carbon and waste disposed	Accommodates to 4 different climate regions	There are spreadsheets and some formulas to determine the model parameters which decrease the ease of operation
EPER Germany	$M_e = M \times BDC \times BDC_t \times F \times D \times C$	Zero order; based on the proportion of degradable carbon and waste amount	Estimates LFG generation independent of the amount of substrate remaining or the amount of biogas already generated	Roughly predicts LFG generation from landfills under operation, but not closed landfill sites
SWANA zero order	$Q = \frac{ML_0}{(t_0 - t)}$	Zero order; based on time, CH ₄ generation potential, and weight		
SWANA first order	$Q = ML_0 e^{-kt}$	First order	Consider the effect of waste age on LFG generation	
LandGEM	$Q_{CH_4} = \sum kL_0M_i(e^{-kt})$	First order; based on the waste composition in the US, non-hazardous wastes, inert materials	User-friendly datasheet	Confusing and complicated mathematics
TNO	$\alpha_t = \zeta 1.87AC_0k_1e^{-k_1t}$	First order; based on the carbon content of the waste	The model exists itself as a publication on paper	Data about the waste organic content is not complete
GasSim		First-order multiphase model	Calculation modules in the program are secured	There is no full set of equations available in the manual
EPER France	$FE_{CH_4} = \sum FE_0 \times (\sum A_i \times P_i \times k_i \times e^{-k_i t})$	First-order multiphase model	The model consists of a simple fill-in table	Although in the spreadsheet it is solved, there is no match between the dimensions of the left and right hand sides of the equation The normalization factor is not considered in the spreadsheet

Table 14 continued

Model name	Formula	Assumptions	Advantages	Disadvantages
Afvalzorg	$a_t = \xi \sum_{i=1}^3 1.87AC_{0,i}k_{i,t}e^{-k_{i,t}t}$	First-order multiphase model; based on the waste characteristics in Netherlands Waste is classified into three categories in terms of degradation rate	Freeware model; available on demand	For some categories, no carbon content or organic matter data is available
LFGGEN	$Q_s = L_0 [2k / (k(t_p - t_0) + 2)] k = (-\ln 0.01) / (t_{99} - t_p)$	Methanogenesis is followed by a lag phase The Methanogenesis first phase follows a linearly increasing generation rate	Considers the lag time to establish anaerobic conditions	
Mexico	$Q_M = \sum_{i=1}^n 2kL_0M_i(e^{-kt})$	First order; CH ₄ generation potential and degradation rate are determined based on the precipitation; based on the waste composition in the US	User-friendly datasheet; a lag of one year is considered for the CH ₄ generation	The default k-values are based on a limited amount of data from only two landfills The model uses an outdated version of the LandGEM equation
Halvadiakis		Based on the carbon mass balance from the solid carbon to carbon in CH ₄		Complex mathematical model; too complicated to be calibrated and implemented
Numerical	$f_1 = k_1 \sum \text{Amn}$	Considers a techniques called “WRM”	Appropriate for every landfill; precise outcomes; remarkably efficacious	

degrading the MSW. The model has also considered the spatial moisture content and spatial variation of the density in different landfill depth values. The optimum pH and temperature that improve the biodegradation have also been incorporated into the model. They reported that this model could be applied to any sites that provide appropriate proportion of heterogeneity of the MSW. They introduced heterogeneity as the percentage of rapidly, moderately, slowly, and non-biodegradable fraction of the MSW.

In brief, different models have different applications as well as different assumptions, advantages, and disadvantages. Therefore, different physical, chemical, and biological aspects of the waste degradation and LFG generation should be taken into account while selecting an appropriate model to obtain respectively precise outcomes.

5 Conclusions and recommendations

Several investigations have been conducted on estimating the LFG generation from sanitary landfills in the literature. These estimations are mainly based on Monod first-order kinetic, which are well known as first-order decay models. In these models, there is a linear relationship of the maximum gas generation potential per waste weight unit as well as an exponential relationship of the waste degradation rate and time.

Zero-order models assume the gas generation rate to be constant versus time. This assumption is the main reason for the significant inaccurate outcomes of these models. Complex mathematical models are based on the carbon mass balance in CH_4 generation chain consisting of solid carbon to aqueous carbon, carbon in acidogenic biomass, carbon in methanogenic biomass, carbon in acetate, carbon in CO_2 , and carbon in CH_4 . Numerical models are also found to be powerful implements to estimate CH_4 generation from landfills and WRM is typically applied in these models for simplicity.

Although the research focus on the estimation of the LFG via modelling has increased over the last decade, there are still several research gaps in the literature that should be taken into account. In most studies, the field measurement data and consequently the modelling are based on the LFG collected from the gas collection systems, and is not based on the actual gas generation

rate in the landfills. Therefore, more in-depth research is required to evidently distinguish between the actual data and the estimations from modelling. Besides, in the landfill sites that are installed with biocovers, biofilters, or biowindows, a proportion of CH_4 is oxidized through the landfill cover soils due to the microbial activity. Since none of the models developed so far has considered CH_4 oxidation, further research should be carried out to incorporate its effect in the modelling basic concepts. In addition, most of the studies focused on using the empirical models to estimate LFG generation rate, and less attention has been paid to the application of the numerical models. However, the recent studies have shown that the numerical models are much closer to the actual collected data than the empirical models. Therefore, it is recommended that more investigations should be carried out on developing new numerical models.

Acknowledgements This research acknowledges the financial support by the Natural Sciences and Engineering Research Council of Canada (NSERC RGPIN-2014-05510).

References

- Afshar H (2002) Finite elements and approximation, Chapter 2. Iranian University of Science and Technology, Tehran
- Amini HR, Reinhart DR (2011) Regional prediction of long-term landfill gas to energy potential. *Waste Manag* 31(9):2020–2026
- Amini HR, Reinhart DR, Mackie KR (2012) Determination of first-order landfill gas modeling parameters and uncertainties. *Waste Manag* 32(2):305–316
- Barlaz MA, Schaefer DM, Ham RK (1989) Bacterial population development and chemical characteristics of refuse decomposition in a simulated sanitary landfill. *Appl Environ Microbiol* 55(1):55–65
- Barlaz MA, Ham RK, Schaefer DM (1990) Methane production from municipal refuse: a review of enhancement techniques and microbial dynamics. *Crit Rev Environ Control* 19(6):557–584
- Barlaz MA, Eleazer WE, Odle WS, Qian X, Wang YS (1997) Biodegradative analysis of municipal solid waste in laboratory-scale landfills. EPA-600/SR-97/071, US Environmental Protection Agency
- Barlaz MA, Chanton JP, Green RB (2009) Controls on landfill gas collection efficiency: instantaneous and lifetime performance. *J Air Waste Manag Assoc* 59(12):1399–1404
- Bentley HW, Smith SJ, Schrauf T (2005) Baro-pneumatic estimation of landfill gas generation rates at four operating landfills. In: SWANA 10th annual landfill gas symposium and solid waste manager, Boulder
- Bergin M, Heavey M, Dennison G (2005) Landfill gas generation and management in a deepfill dry commercial and

- industrial waste landfill in Ireland. In: Tenth international waste management and landfill symposium, Sardinia
- Bilgili MS, Demir A, Özkaya B (2007) Influence of leachate recirculation on aerobic and anaerobic decomposition of solid wastes. *J Hazard Mater* 143(1):177–183
- Bonori B, Pasquali G, Bergonzoni M (2001) Landfill gas production valued with a mathematical method. In: Eighth international waste management and landfill symposium, Sardinia
- Budka A, Aniel D, Puglierin L, Stoppioni E (2007) Bioreactor and conventional landfill: LFG modeling after three management years of two compared cells in Sonzay, France. In: Eleventh international waste management and landfill symposium, Sardinia
- Cakir AK, Gunerhan H, Hepbasli A (2016) A comparative study on estimating the landfill gas potential: modeling and analysis. *Energy Source Part A Recovery Util Environ Eff* 38(16):2478–2486
- Chakma S, Mathur S (2016) Modelling gas generation for landfill. *Environ Technol*. doi:[10.1080/09593330.2016.1231226](https://doi.org/10.1080/09593330.2016.1231226)
- Cohen B (2016) Modelling approaches for greenhouse gas emissions projections from the waste sector. *Sustain Prod Consum* 10:15–20
- Corti A, Lombardi L, Frassinetti L (2007) Landfill gas energy recovery: economic and environmental evaluation for a case study. In: Eleventh international waste management and landfill symposium, Sardinia
- Donovan SM, Bateson T, Gronow JR, Voulvoulis N (2010) Modelling the behaviour of mechanical biological treatment outputs in landfills using the GasSim model. *Sci Total Environ* 408(8):1979–1984
- El-Fadel M, Findikakis AN, Leckie JO (1989) A numerical model for methane production in managed sanitary landfills. *Waste Manag Res* 7:31–42
- EMCON Associates (1980) Methane generation and recovery from landfills. Ann Arbor Science Publishers Inc., Ann Arbor, Michigan
- Faour AA (2003) First-order kinetic gas generation model parameters for wet landfills. University of Central Florida, Orlando
- Faour AA, Reinhart DR, You H (2007) First-order kinetic gas generation model parameters for wet landfills. *Waste Manag* 27:946–953
- Findikakis AN, Leckie JO (1979) Numerical simulation of pass flow in sanitary landfills. *J Environ Eng* 115:927–945
- Findikakis AN, Papelis C, Halvadakis CP, Leckie JO (1988) Modeling gas production in managed sanitary landfills. *Waste Manag Res* 6(1):115–123
- Fredenslund AM, Lemming G, Scheutz C, Kjeldsen P (2007) Implementing biocover on Fakse landfill: landfill characterization, gas production modeling and mapping spatial variability in emissions. In: Eleventh international waste management and landfill symposium, Sardinia
- Gardner N, Probert SD (1993) Forecasting landfill gas yields. Science Publishers Ltd., Cambridge, pp 131–163
- Garg A, Achari G, Joshi RC (2006) A model to estimate the methane generation rate constant in sanitary landfills using fuzzy synthetic evaluation. *Waste Manag Res* 24:363–375
- Gebert J, Groengroeft A, Miehlich G (2003) Kinetics of microbial landfill methane oxidation in biofilters. *Waste Manag* 23:609–619
- Golder Associates (2006) GasSim Manual Version 2.0, Stanton on the Worlds. Nottingham Scientific Ltd., Nottingham
- Gregory RG, Attenborough MG, Hall CD, Deed C (2003) The validation and development of an integrated landfill gas risk assessment model GasSim. In: Ninth international waste management and landfill symposium, Calgary
- Harries CR, Cross CJ, Smith R (2001) Development of a biochemical methane potential (BMP) test and application to testing of municipal solid waste samples. In: Eighth international waste management and landfill symposium, Calgary
- Hartz KE (1982) Gas generation rates of landfill samples. *Conserv Recycl* 5:133–147
- Huitric RL, Rosales MA (2005) Determining the reliability of landfill methane projections. In: SWANA 10th annual landfill gas symposium and solid waste manager, Boulder
- IPCC (1996) IPCC guideline for national greenhouse gas inventories. IPCC, Geneva, Switzerland
- IPCC (2006) Guidelines for national greenhouse gas inventories: intergovernmental panel on climate change. Waste, vol 5. IGES
- Ishii K, Furuichi T (2013) Estimation of methane emission rate changes using age-defined waste in a landfill site. *Waste Manag* 33(9):1861–1869
- Kamalan H (2009) Modelling of greenhouse gasses emission out of urban solid waste landfills in arid and semi-arid region. Ph.D. Thesis, K.N. University of Technology, Tehran
- Kamalan H (2016) A new empirical model to estimate landfill gas pollution. *J Health Sci Surveill Syst* 4(3):142–148
- Karanjekar RV, Bhatt A, Altouqui S, Jangikhatoonabad N, Durai V, Sattler ML, Hossain MS, Chen V (2015) Estimating methane emissions from landfills based on rainfall, ambient temperature, and waste composition: the CLEAN model. *Waste Manag* 46:389–398
- Keely DKH (1994) A model for predicting methane gas generation from MSW landfills. M.Sc. Thesis, Department of Civil and Environmental Engineering, University of Central Florida, Orlando
- Krause MJ, Chickering GW, Townsend TG (2016) Translating landfill methane generation parameters among first-order decay models. *J Air Waste Manag Assoc* 66(11):1084–1097
- Kumar S, Nimchuk N, Kumar R, Zietsman J, Ramani T, Spiegelman C, Kenney M (2016) Specific model for the estimation of methane emission from municipal solid waste landfills in India. *Bioresour Technol* 216:981–987
- Lobo AGC (2003) Moduelo 2: a tool to be used to evaluate municipal solid waste landfills contamination. Ph.D. Thesis, University of Cantabria
- Machado SL, Carvalho MF, Gourc JP, Vilar OM, Nascimento JCF (2009) Methane generation in tropical landfills: simplified methods and field results. *Waste Manag* 29(1):153–161
- Mahar RB, Sahito AR, Yue D, Khan K (2016) Modeling and simulation of landfill gas production from pretreated MSW landfill simulator. *Front Environ Sci Eng* 10(1):159–167

- McBean EA, Rovers FA, Farquhar GJ (1995) Solid waste landfill engineering and design. Prentice Hall PTR, Englewood Cliffs
- Mehta R, Barlaz MA, Yazdani R, Augenstein D, Bryars M, Sinderson L (2002) Refuse decomposition in the presence and absence of leachate recirculation. *J Environ Eng* 128(3):228–236
- Mor S, Ravindra K, De-Visscher A, Dahiya RP, Chandra A (2006) Municipal solid waste characterization and its assessment for potential methane generation: a case study. *Sci Total Environ* 371:1–10
- Nastev M (1998) Modelling landfill gas generation and migration in sanitary landfills and geological formations. Ph.D. Thesis, Laval University, Quebec
- Ogor Y, Guerbois M (2005) Comparison of landfill methane emission models: a case study. Tenth international waste management and landfill symposium, Sardinia
- Oonk H, Weenk A, Coops O, Luning L (1994) Validation of landfill gas formation models. TNO Institute of Environmental and Energy Technology Report, Grontmij, Netherlands
- Ozakaya B, Demir A, Bilgili MB (2006) Neural network prediction model for the methane fraction in biogas from the field-scale landfill bioreactors. *Environ Model Soft* 22:815–822
- Penteado R, Cavalli M, Magnano E, Chiampo F (2012) Application of the IPCC model to a Brazilian landfill: first results. *Energy Policy* 42:551–556
- Pierce J, LaFountain L, Huitric R (2005) Landfill gas generation and modeling manual of practice. Solid Waste Association of the North America (SWANA)
- Reinhart DR, Al-Yousfi AB (1996) The impact of leachate recirculation on municipal solid waste landfill operating characteristics. *Waste Manag Res* 14:337–346
- Reinhart R, Faur A (2004) First order kinetic gas generation model parameters for wet landfills. University of Central Florida, Orlando
- Sabour M, Kamalan H (2006) Energy element (methane) recovery from municipal solid waste treatment facilities. In: Proceedings of the biomass and waste to energy symposium, Venice
- Sabour MR, Mohamedifard A, Kamalan H (2007) A mathematical model to predict the composition and generation of the hospital wastes in Iran. *Waste Manag* 27:584–587
- Scharff H, Jacobs J (2006) Applying guidance for methane emission estimation for landfills. *Waste Manag* 26:417–429
- Scheepers MJJ, van Zantan B (1994) Handleiding stortgaswinning. Adviescentrum Stortgas, Apeldoorn
- Shariatmadari N, Sabour M, Kamalan H, Mansouri A, Ablofatzade M (2007) Applying simple numerical model to predict methane emission from landfill. *J Appl Sci* 7:1511–1515
- Sponza DT, Ağdağ ON (2004) Impact of leachate recirculation and recirculation volume on stabilization of municipal solid wastes in simulated anaerobic bioreactors. *Process Biochem* 39(12):2157–2165
- Steger AG, Murray DL (2003) User's manual Mexico landfill gas model. EPA, Washington
- SWANA (1998) Comparison of models for predicting landfill methane recovery. Publication No. GR-LG 0075, The Solid Waste Association of the North America (SWANA), Dallas
- Tchobanoglous G, Theisen H, Vigil S (1993) Integrated solid waste management. McGraw-Hill, New York
- Thompson S, Sawyer J, Bonam R, Valdivia JE (2009) Building a better methane generation model: validating models with methane recovery rates from 35 Canadian landfills. *Waste Manag* 29:2085–2091
- Thorneloe SA, Reisdorph A, Laur M, Pelt R, Bass RL, Burklin C (1999) The US Environmental Protection Agency's landfill gas emissions model (LandGEM). In: Proceedings of the Sardinia 99, sixth international landfill symposium. Environmental impact, (SILSVEI99), aftercare and remediation of landfills, vol IV. pp 11–18
- Tintner J, Kühleitner M, Binner E, Brunner N, Smidt E (2012) Modeling the final phase of landfill gas generation from long-term observations. *Biodegradation* 23(3):407–414
- Tolaymat TM, Green RB, Hater GR, Barlaz MA, Black P, Bronson D, Powell J (2010) Evaluation of landfill gas decay constant for municipal solid waste landfills operated as bioreactors. *J. Air Waste Manag Assoc* 60(1):91–97
- US EPA (2016) Inventory of US greenhouse gas emissions and sinks: 1990–2014. EPA 430-R-16-002, Washington
- Van Heut RE (1986) Estimating landfill gas yields. In: Proceedings GRCDA 9th international landfill gas symposium (GILS86), Newport Beach. pp 92–120
- Willumsen H, Terraza H (2007) CDM landfill gas projects—World Bank Report. World Bank Workshop, Washington