



Journal of Environmental Science and Technology

ISSN 1994-7887

science
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A Review on Available Landfill Gas Models

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ABSTRACT

Landfill Gas (LFG) is classified as the main source of methane, a greenhouse gas, caused by human activities. On the other hand, methane is an important energy element. Also, it can cause fires in landfill. On these bases, estimation of methane generated out of landfills has been highly important to scientists, decision makers and owners of landfills. The purpose of this study is to review most used models which predicts LFG. As a result, these models can be classified in zero order, first order and second order decay, mathematical and numerical models. First order decay models, which are used more all over the world, has been considered in more details as multiphase models which result in more appropriate estimations. However, numerical models can lead to more accurate results.

Key words: Landfill gas, models, methane, emission

INTRODUCTION

Environment and natural resources can be polluted and consequently human beings, animals and plants can be impacted (Sabour *et al.*, 2007). So, waste management plays a key role in human's life (Kamalan, 2007). Sanitary landfilling, a common method for the disposal of solid waste (Chen *et al.*, 2003), is recognized as an important source of methane which is the major component of greenhouse gases (Kamalan, 2009). Atmospheric methane concentrations have doubled over the last 200 years and continue to rise, although the rate of increase is slowing. By mass, methane has 21 times the global warming potential of carbon dioxide over a 100 year time frame (Shariatmadari *et al.*, 2007). On this basis, There are lots of regulatory to manage and/or estimate the landfill methane gas such as the Protocol on Pollutants Release and Transfer Registers (also known as PRTRs- or Kiev-protocol) (Scharff and Jacobs, 2006). In addition, methane has got a great deal amount of energy which encourages decision makers and scientists to estimate and use it (Sabour and Kamalan, 2006).

Above mentioned issues have led to develop landfill gas estimations models. Most of these models have been developed on Monod equation, first order decay, such as TNO, LandGEM, Gassim, Afvalzorg, EPER, IPCC, LFGEEN. Some of them are based on Monod equation, zero order decay, such as EPER France. Few models to predict methane from landfills are based on the sequential biological growth such as Halvadakis model (Nastev, 1998). Some newly developed models are numerical ones such as weighted residual and neural network (Ozakaya *et al.*, 2006; Shariatmadari *et al.*, 2007). This study aims to review all these available models, their advantages and disadvantages and provide guidance for scientists, decision makers and researchers.

AVAILABLE MODELS

There are two particular approaches for mathematical presentation of the gas production rate: (1) gas production rate is given as a simple empirical function or as a combination of simple functions of an overall kinetic parameter, (2) models where the gas production rate is given as a complex sum of mathematical functions representing the individual kinetics of the considered physico-chemical processes occurring during refuse biodegradation and (3) numerical models which interpret gas production in digits.

As it has been mentioned, some models work with overall kinetic parameter which is the most common type of models encountered in the literature (Cheremisinoff and Morresi, 1976; Findikakis and Leckie, 1979; Hartz and Ham, 1982; EMCON Associates, 1982; Van Heut, 1986; Gardner and Probert, 1993). The overall kinetic parameter is empirically adjusted to match the observed production rates. A start-up period during which little or no methane is produced may be assumed, it is followed by a period of active methane production represented mostly by linear or exponential relations, or their combinations. Figure 1a and b show this issue at a glance. The cumulative gas production can then be obtained as a sum of the gas production rates over the active production period and should correspond to the assumed initial production potential of the landfill.

A theoretical approach for the derivation of most of these relatively simple models is based on the general kinetic expression for the biodegradation processes well known as Monod's equation as following form:

$$\frac{dC}{dt} = \frac{Kx C}{K_c + C} \tag{1}$$

where, C is the remaining concentration of substrate at time t, such as organic matter, organic carbon (mass of carbon per unit volume/mass of refuse), x is the concentration of microorganisms

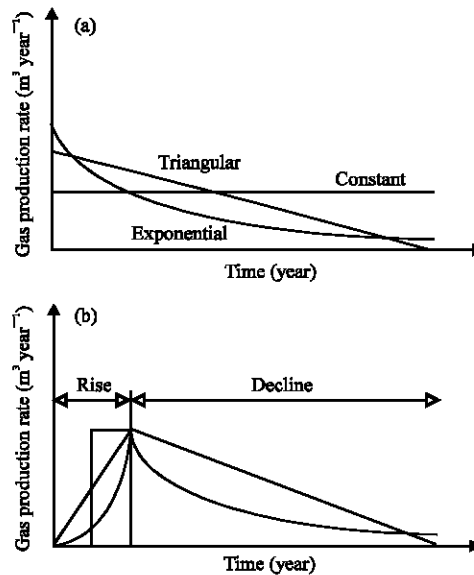


Fig. 1: Presentation of gas production rate with time, (a) simple functions and (b) combinations (Nastev, 1998)

(kg microorganisms per m³ refuse), K is the maximum rate of substrate utilization per kg of microorganisms, K_c is the refuse concentration at which the rate is one-half the maximum rate of substrate utilization.

Monod's equation can be approximated by the following functions in the two extreme cases: (1) zero-order reaction with respect to substrate concentration: for large C, the substrate utilization rate dC/dt is constant if the concentration of the microorganisms, x, remains constant and (2) first-order reaction with respect to the substrate concentration: for small C and assuming again constant concentration of microorganisms, x = constant, the substrate utilization rate is then a linear function of the substrate concentration.

Zero order: In this kind of model, biogas generated from landfills is remained steady against time. On this basis, waste age and waste type has no effect on gas production.

EPER Germany: The EPER model used in Germany is a zero order model as shown in Eq. 2 (Scharff and Jacobs, 2006).

$$M_e = M \times BDC \times BDC_f \times F \times D \times C \quad (2)$$

where, M_e is amount of diffuse methane emission, M is annual amount of landfilled waste, BDC is proportion of biodegradable carbon (0.15), BDC_f is proportion of biodegradable carbon converted (0.5), F is calculation factor of carbon converted into CH₄ 1.33, D is collection efficiency: active degassing 0.4, no recovery 0.9, active LFG recovery and cover 0.1 and C is methane concentration 0.50.

In fact, if a constant amount of waste of constant composition is disposed in a landfill, the result is the same as for a first-order degradation model.

SWANA zero order: SWANA has developed a zero order model in which kind of waste has been considered as Eq. 3 (SWANA, 1998):

$$Q = \frac{ML_o}{(t_o - t_f)} \quad (3)$$

where, Q is methane generation rate, M is the waste in place, L_o is methane generation potential, t_o is lag time and t_f is time to end point of generation.

IPCC: IPCC provides a zero order model based on population, degradable material within the waste and methane correction factor as represented in Eq. 4 (IPCC, 1996):

$$Q = (MSWT \times MSWF \times MCF \times DOC \times DOCF \times F \times 16/12 R) \times (1 - OX) \quad (4)$$

where, MSWT is total MSW generated, MSWF is fraction of MSW disposed to solid waste disposal sites, MCF is methane correction factor, DOC is degradable organic carbon, DOCF is fraction DOC dissimilated, F is fraction of CH₄ in landfill gas (default is 0.5), R is recovered CH₄ and OX is oxidation factor (fraction-default is 0).

Table 1: MCF parameter in IPCC model

Type of site	Methane Correction Factor (MCF) default values
Managed	1.0
Unmanaged-deep (≥ 5 m waste)	0.8
Unmanaged-shallow (< 5 m waste)	0.4
Unmanaged-uncategorized SWDSs	0.6

Table 2: DOC parameter in IPCC model

Waste stream	DOC (%) (by weigh)
Paper and textiles	40
Garden and park waste and other (non food) organic mater	17
Food waste	15
Wood and straw waste ^a	30

^aExcluding lignin c

Total MSW (MSWT) can be calculated from Population (thousand persons) multiple by annual MSW generation rate. Per capita MSW generation rates are provided for many countries and regions in related tables. The components of MSW may vary from country to country. These differences can play an important role in the resulting emissions estimate, as each waste stream may have a different DOC content and hence a different CH₄ generation potential. In general, countries should include the following waste streams in their estimate of total MSW generated.

- Household waste
- Yard and garden waste
- Commercial or market waste

The MCF and DOC have been calculated for different situation and classes as shown in Table 1 and 2.

First order: Just about all available and worldwide-used models which predict biogas from landfills are among ones developed based on first order decay models. These models have been considered quality of waste (i.e., moisture content, carbon content, age of waste and ability of waste to be digested), waste quantity and condition of landfill (i.e., climate, temperature, precipitation) implicitly. In the order words, the effect of depletion of carbon in the waste through time is accounted for in a first-order model (Ozakaya *et al.*, 2006).

First order models always assume a direct relation with carbon content of the waste and exponential function of decay rate by time against generated methane (Gardner and Probert, 1993).

SWANA: The effect of waste age on gas production is incorporated in the first order model. For each unit amount of waste, landfill gas generation rates decline exponentially. This model can be represented by Eq. 5 (SWANA, 1998):

$$Q = ML_0 e^{-kt} \tag{5}$$

where, k is first-order rate constant.

TNO: TNO model calculates LFG generation based on degradation of organic carbon in the waste as shown in Eq. 6 (Scharff and Jacobs, 2006):

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

where α_t is landfill gas production at a given time, ζ is dissimilation factor 0.58, 1.87 conversion factor, A is amount of waste in place, C_o is amount of organic carbon in waste and k_1 degradation rate constant 0.094.

Amount of organic carbon in waste (C_o) has been classified in eight categories as contaminated soil, construction and demolition waste, shredder waste, street cleansing waste, contaminated soil, construction and demolition waste, shredder waste, street cleansing waste, sewage sludge and compost, coarse household waste, commercial waste, household waste, sewage sludge and compost, coarse household waste, commercial waste, household waste as 11, 11, 130, 90, 90, 130, 11 and 130 kg^C Mg⁻¹, respectively.

LandGEM: USEPA has developed software with the name of LandGEM which uses almost the same formula for municipal solid waste. LandGEM uses the first order decomposition rate equation to estimate annual emissions over a specified time period (EPA, 2005) as presented in Eq. 7.

$$Q_{CH_4} = \sum_{i=1}^n k L_o M_i (e^{-k t}) \quad (7)$$

where, M_i is the waste in placed in specific time of t.

US-EPA protocols state that the composition of waste used in the model reflects US waste composition of MSW, inert material and other non-hazardous wastes. For a landfill containing non-biodegradable waste (i.e., inert material), such as ash from waste combustion, this portion may be subtracted from the waste acceptance rates. LandGEM recommends subtracting inert materials only when documentation is provided and approved by a regulatory authority. This is not recommended for sites that are typical MSW landfills containing a range of waste that may or may not be degradable. LandGEM provides methane generation constant and potential for both CAA (Clean Air Act) and AP42 standards. It is recommended to use AP42 default values for standard landfills. CAA default values have a high methane generation potential (L_o) of 180 m³CH₄ Mg⁻¹ waste (Scharff and Jacobs, 2006).

LandGEM is based on the first-order decomposition rate equation and the inputs are:

- Design capacity of the landfill
- Amount of waste in place or the annual acceptance rate
- The methane generation rate constant k and methane generation potential L_o .
- The concentration of total and individual NMOC
- The years of waste acceptance
- Acceptance of hazardous waste at the landfill

Default values for k and L_o can be used or site-specific values can be developed through field test measurement.

Outputs of LandGEM are as follows (Thorneloe *et al.*, 1999):

- Emission rate for methane, NMOCs and selected air pollutants can be estimated annually over the life of the landfill and for a specific number of years after the landfill closure
- Two sets of default values for emissions calculations are incorporated in the model. The first set is for determining the applicability of Federal regulatory requirements (Clean Air Act defaults) and another for developing emission inventories (AP-42 defaults)
- Landfill closure estimates based on the landfill capacity and waste acceptance rate
- Emissions for individual pollutants
- Graphs of emissions for individual pollutants

GasSim: GasSim uses first order decay equation based on a multiphase model described by Scheepers and van Zanten (1994). There is no complete set of equations used in GasSim in the manual Version 2.0 (Golder Associates, 2006). Calculation modules in the program are protected. It was therefore not possible to reproduce the equations in this study. This model requires waste input in Mg and the specific breakdown during the particular year of disposal. The waste categories and their carbon content used in the GasSim multiphase model are presented in Table 3. To give an impression, degradation rates, k values and fractions of the GasSim multiphase model are shown in Table 4 (Scharff and Jacobs, 2006).

Afvalzorg: Afvalzorg is another multiphase model on predicting LFG production which takes advantage of considering 8 waste categories and three fractions. Each fraction is contemplated separately for purposes of LFG production estimation. In the Afvalzorg multiphase model, eight waste categories and three fractions are distinguished. For some waste categories, no organic matter

Table 3: Waste categories and organic carbon content of the GasSim

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

Table 4: Degradation rate, k values and fractions of the GasSim multiphase model

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

Table 5: Organic matter content used in the Afvalzorg multi-phase model

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

^aOnly rapidly, moderately and slowly degradable organic matter has been taken into consideration, The total organic matter content is higher than the sum of these three categories due to the presence of organic matter that is not considered biodegradable under anaerobic conditions. Examples are hum substances, lignin and plastics

or carbon content data were available (Scharff and Jacobs, 2006). The multiphase model is a first order model and can be described mathematically by Eq. 8. Amount of organic content has been shown in Table 5 (Shariatmadari *et al.*, 2007):

$$\alpha_t = \zeta \sum_{i=1}^3 1.87 A C_{0,i} k_{1,i} e^{-k_{1,i}t} \tag{8}$$

where, α_t is landfill gas formation at a time t , ζ is dissimilation factor, i is waste fraction with degradation rate $k_{1,i}$, A is amount of waste in place, $k_{1,i}$ is degradation rate constant of fraction i (which is between 0.03 and 0.231).

EPER France: Methane emissions estimates for landfill cells connected or not connected to an LFG recovery system using a multiphase model (ADEME version 15/12/2002) and the LFG recovery efficiency is the concept of EPER France model. The formulation of this model is multiphase one as Eq. 9.

$$FE_{CH_4} = \sum_x FE_0 \times \left(\sum_{1,2,3} A_i \times p_i \times k_i \times e^{-k_i t} \right) \tag{9}$$

where, FE_{CH_4} is annual methane production, FE_0 is methane generation potential, p_i is waste fraction with degradation rate k_i , A_i is normalization factor.

The dimensions left and right in the equation do not match. It would seem that the amount of waste in $Mg \text{ year}^{-1}$ is missing on the right-hand side. In the spreadsheet itself, the annual amounts of waste are used in the calculation. Although, a normalization factor is given in the equation, it seems that this factor is not included in the spreadsheet. The model describes three categories of waste and every category has a specific methane generation capacity per Mg of waste. The three categories, their specific methane generation capacities are shown in Table 6. Fractions and k values for each waste category are shown in Table 7 (Scharff and Jacob, 2006).

Table 6: Waste categories and methane generation capacity of the ADEME model

Category	Methane generation (m ³ CH ₄ Mg ⁻¹)	Waste categories ADEME
1	100	MSW, sludges, yard waste
2	50	Industrial waste, commercial waste, biologically pre-treated waste
3	0	Inert waste, non-biodegradable waste

Table 7: Fractions and k values of the ADEME multi-phase model

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

Table 8: Methane generation rate (k)

k (year ⁻¹)	Annual precipitation (mm year ⁻¹)
0.040	0-249
0.050	250-499
0.065	500-999
0.080	At least 1000

Table 9: Potential methane generation capacity (L₀)

L ₀ (m ³ t ⁻¹)	Annual precipitation (mm year ⁻¹)
60	0-249
80	250-499
84	At least 500

Mexico: The model assumes a one-year time lag between placement of waste and LFG generation. For each unit of waste, after one year the model assumes that methane generation decreases exponentially as the organic fraction of waste is consumed. For sites with known (or estimated) year-to-year solid waste acceptance rates, the model estimates the LFG generation rate in a given year using the Eq. 10, which is published in Title 40 of the US Code of Federal Regulations (CFR) Part 60 (Stege and Murray, 2003). Mexico LFG model can be described as Eq. 10 (Stege and Murray, 2003):

$$Q_M = \sum_{i=1}^n 2kL_0M_i(e^{-kt}) \quad (10)$$

The Mexico LFG model requires site-specific data for all the information needed to produce generation estimates, except for the k and L₀ values. In fact, the model provides default values for k and L₀. The default values are based on site specific data gathered from representative landfills in Mexico and the relationship between the k and L₀ values and average annual precipitation observed at landfills in the US (Stege and Murray, 2003) as presented in Table 8 and 9, respectively.

The composition of Municipal Solid Waste (MSW) landfill gas is assumed by the model to be about 50% methane (CH₄) and 50% other gases, including carbon dioxide (CO₂) and trace amounts of other compounds.

LFGGEN: This model was firstly developed at the University of Central Florida (Keely, 1994). The assumptions for this model are: (1) methanogenesis is preceded by a lag phase, (2) the first stage of methanogenesis is represented by a linearly increasing generation rate and (3) the second stage of methanogenesis is represented by first-order kinetics, with an exponentially decreasing generation rate. The model has some additional features, which are (Reinhart and Faour, 2004):

- Methods of analysis provided are the following: theoretical stoichiometric generation of methane and carbon dioxide, biodegradability factors, Biochemical Methane Potential (BMP) and EPA Tier 3
- Biodegradable solid waste is divided into eleven categories
- Moisture is classified into three categories; wet, moderate and dry
- Biodegradability rates are classified into three categories; rapid, moderate and slow

Biodegradability rates are also a function of moisture.

This model includes a time delay t_0 , to establish anaerobic conditions, followed by a linear increase to a specific peak rate, Q_s , that occurs at the end of year, t_p . After the peak, the generation rate decreases exponentially from the peak to a nearly zero rate at the end of the prescribed biodegradation time, t_{99} , which is the time for the gas generation rate to drop to one percent of the peak rate.

The model assumes that the characteristic times t_0 , t_p and t_{99} , vary with the type of waste and moisture condition. The specific peak rate is a function of these time and methane potential as shown in Eq. 11 (Reinhart and Faour, 2004).

$$Q_s = L_0 \frac{2k}{k(t_p - t_0) + 2} \quad (11)$$

For the second phase of methanogenesis, the biodegradation constant k is related to the assumed times as represented in the Eq. 12.

$$k = \frac{-\ln 0.01}{t_{99} - t_p} \quad (12)$$

Second order: The second-order model describes the complex reactions during degradation of the waste, using a large number of first-order reactions with different rates. Being a complex system of different reactions, landfill gas generation can be modeled using the second order kinetics model (Reinhart and Faour, 2004).

Other methods

Complex mathematical models: These models represent explicitly in a complex mathematical function some or most of the known important physical, chemical and biological variables

(composition, moisture, content, temperature, absorption, adsorption, volatilization, evaporation, dilution, filtration, complexation, precipitation, neutralization, oxidation, reduction, etc.) which affects the production rate. Although the importance of these variables is known, it is not possible to describe the gas production rate with any certainty without a detailed characterization of the actual conditions inside the landfill. This requires a significant amount of measurements and a very detailed analysis (Nastev, 1998).

The Halvadakis model (El-Fadel *et al.*, 1989), as a representative complex mathematical model for landfill gas production, is based on the sequential biological growth. The very complex microbial landfill ecosystem is represented by a system of first order equations. They are given in terms of carbon sources, pathways and sinks, describing the hydrolysis of the hydrolysable and biogasifiable waste components, utilization of the aqueous carbon for growth of the acidogenic and methanogenic biomass, utilization of acetate and consequent generation of methane and carbon dioxide. This is equivalent to a simplified microbial food chain. However, this model neglects the methane generation from the reduction of carbon dioxide with hydrogen which, we have seen, represents 25-30% of the total methane produced. Carbon is given in seven possible forms in the corresponding mass balance equations as follows:

Solid carbon,

$$\frac{dC_{(s)}}{dt} = -K_{hs}C_s \quad (13)$$

Aqueous carbon,

$$\frac{dC_{(aq)}}{dt} = \sum_{i=1}^3 K_{ha} C_{(s)i} - \frac{1}{Y_A} \mu_A K \frac{C_{(aq)}}{k_{sa} - C_{(aq)}} C_{xa} \quad (14)$$

Acidogenic biomass carbon,

$$\frac{dC_{(xa)}}{dt} = \left(\mu_A \frac{C_{(aq)}}{k_{sa} - C_{(aq)}} - K_{da} \right) C_{xa} \quad (15)$$

Methanogenic biomass carbon,

$$\frac{dC_{(xm)}}{dt} = \left(\mu_m \frac{C_{(Ac)}}{k_{sm} + C_{(Ac)}} - K_{dm} \right) C_{xm} \quad (16)$$

Acetate carbon,

$$\frac{dC_{(Ac)}}{dt} = Y_{Ac} \left(\frac{1 - Y_{Ac}}{Y_{Ac}} \mu_A \frac{C_{(aq)}}{k_{sa} + C_{(aq)}} + K_{da} \right) - \frac{1}{Y_m} \mu_m \frac{C_{(Ac)}}{k_{sm} - C_{(Ac)}} C_{xm} \quad (17)$$

Carbon in CO₂,

$$\frac{dC_{(CO_2)}}{dt} = (1 - Y_{Ac}) \left(\frac{1 - Y_{Ac}}{Y_{Ac}} \mu_A \frac{C_{(aq)}}{k_{sa} + C_{(aq)}} + K_{da} \right) C_{xa} + (1 - Y_{CH_4}) \left(\frac{1 - Y_m}{Y_m} \mu_m \frac{C_{(Ac)}}{k_{sm} + C_{(Ac)}} + K_{dm} \right) C_{xm} \quad (18)$$

Carbon in CH₄,

$$\frac{dC_{(CH_4)}}{dt} = Y_{CH_4} \left(\frac{1 - Y_m}{Y_m} \mu_m \frac{C_{(Ac)}}{k_{sm} + C_{(Ac)}} + K_{dm} \right) C_{xm} \quad (19)$$

Numerical: Numerical method is strong tool to simulate and model all phenomena if there is a good general understanding of them (Afshar, 2002). So, it can be used to estimate methane generation in a simpler method. Weighted Residual Method (WRM) can be used in this regard successfully and the result on a real landfill with few observed data has showed a reasonable perdition. For each landfill with few methane measurements, Eq. 20 can be used. With some try and error all unknown parameters can be obtained (Shariatmadari *et al.*, 2007).

$$\iint_{\text{Domain}} w_p(G - \Psi) dtdw = \iint_{\text{Domain}} a_{mn}(w_p \sum_{n,m=1} N_{mn}) \Leftrightarrow f_i = k_i \sum a_{mn} \quad (20)$$

where, Ψ is a function to satisfy boundary condition, N is trail function which should be zero on boundaries and a is coefficient which should be determined. The goal of WRM is to choose a_{mn} such that residue (R) becomes small over a chosen domain.

CONCLUSIONS

Several studies have been done to estimate methane production out of municipal landfills. These are mostly based on Monod first order decay equation which are called first order decay models. In all of these models, it is assumed that landfill gas consists of 50% CO₂ and 50% CH₄ which has error. First order models have a linear relation with maximum potential of methane production per weight unit of waste as well as an exponential relation with decay rate and time.

A few models are classified as zero order models in which methane production is assumed to be constant against time. This assumption causes a vivid inaccuracy in the results.

Complex mathematical models which follow the carbon in methane production chain of from solid carbon to aqueous carbon, acidogenic biomass carbon, methanogenic biomass carbon, acetate carbon, carbon in CO₂ and then carbon in CH₄.

Numerical models are strong tools to predict methane emission out of landfills in which weighted residual methods are usually applied.

Table 10: List of different LFG prediction models and their specifications

Models	Formula	Notes
EPER Germany	$M_e = M \times BDC \times BDC_f \times F \times D \times C$	Zero order Based on amount of waste, proportion of biodegradable carbon, biodegradable, ...
SWANA zero order	$Q = \frac{ML_o}{(t_o - t_1)}$	Zero order model Based on weight of waste, time and methane generation potential
IPCC	$Q = (MSWT \times MSWF \times MCF \times DOC \times DOCF \times F \times 16/12 - R) \times (1 - OX)$	Zero order model Based on waste landfilled and degradable organic carbon There are tables and some formula to calculate IPCC model parameters
SWANA	$Q = ML_o e^{-kt}$	First order Based on carbon content, Information on organic content of waste components are not completed
TNO	$\alpha_i = \zeta 1.87 A C_{0,i} k_{1,i} e^{-k_{1,i} t}$	
LandGEM	$Q_{CH_4} = \sum_{i=1}^n k L_o M_i (e^{-k_i t})$	First order Based on US waste composition, inert material and other non-hazardous wastes, User friendly in spreadsheet environment
GasSim	-	First order, multiphase model There in no complete set of equations in the manual Calculation modules in the program are protected
Afvalzorg	$\alpha_i = \zeta \sum_{i=1}^3 1.87 A C_{0,i} k_{1,i} e^{-k_{1,i} t}$	First order, multiphase model Based on Netherlands wastes characteristics Wastes are classifies in 3 categories in terms of decay rate For some waste categories, no organic matter or carbon content data were available
EPER France	$FE_{CH_4} = \sum_k FE_0 \times (\sum_{i,2,3} A_i \times p_i \times k_i \times e^{-k_i t})$	First order, multiphase model Dimensions left and right in the equation do not match in the formula but in the spreadsheet it is solved Normalization factor seems that is not included in the spreadsheet
Mexico	$Q_M = \sum_{i=1}^n 2k L_o M_i (e^{-k_i t})$	First order model Speared sheet environment A year lag in methane production Based on USA waste composition Potential methane generation capacity and decay rate are provided based on precipitation
LFGGEN	$Q_s = L_o \frac{2k}{k(t_p - t_o) + 2}$ $k = \frac{-\ln 0.01}{t_{99} - t_p}$	Methanogenesis is preceded by a lag phase The first stage of methanogenesis is represented by a linearly increasing generation rate The second stage of methanogenesis is represented by first-order kinetics, with an exponentially decreasing generation rate Based on USA waste composition
Halvadakis		Complex mathematical model Follow the carbon from Solid Carbon up to Carbon in CH ₄ Too hard to be calibrated and used
Numerical	$f_i = k_i \sum_{d_{ann}}$	Very effective Accurate results Applicable for each landfill

Table 10 represents all models reviewed in this study including their assumptions, weak points and strength.

REFERENCES

- Afshar, H., 2002. Finite Elements and Approximation. Chapt. 2. Iranian University of Science and Technology, Iran.
- Chen, Y.C., K.S. Chen and C.H. Wu, 2003. Numerical simulation of gas flow around a passive vent in a sanitary landfill. *J. Hazardous Mater.*, 100: 39-52.
- Cheremisinoff, P.N. and A.G. Morresi, 1976. Energy from Solid Wastes. Pollution Engineering and Technology, Marcel Dekker Inc., New York.
- EMCON Associates, 1982. Methane Generation and Recovery from Landfills. Ann Arbor Science Publishers, Michigan.
- EPA, 2005. Landfill Gas Emissions Model (LandGEM). Version 3.02, Eastern Research Group, USA.
- El-Fadel, M., A.N. Findikakis and J.O. Leckie, 1989. A numerical model for methane production in managed sanitary landfills. *Waste Manage. Res.*, 7: 31-42.
- Findikakis, A.N. and J.O. Leckie, 1979. Numerical simulation of gas flow in sanitary landfills. *J. Environ. Eng.*, 115: 927-945.
- Gardner, N. and S.D. Probert, 1993. Forecasting Landfill-Gas Yields. Science Publishers Ltd., England, pp: 131-163.
- Golder Associates, 2006. GasSim Manual Version 2.0, Stanton on the Wolds. Nottingham Scientific Ltd., England.
- Hartz, K.E. and R.K. Ham, 1982. Gas generation rates of landfill samples. *Conservation Recycling*, 5: 133-147.
- IPCC, 1996. IPCC Guideline for National Greenhouse Gas Inventories. IPCC., England.
- Kamalan, H., 2007. Feasibility study of implementation of integrated solid waste management in three Northern Provinces of Iran. Proceedings of the World Congress on Recovery of Materials and Energy Resources Efficiency, Sept. 3-5, Davos, Swiss, pp: 5-5.
- Kamalan, H., 2009. Modeling of greenhouse gases emission out of urban solid waste landfills in arid and semi-arid region (case study: Tehran). Ph.D. Thesis, K.N. Toosi University of Technology.
- Keely, D.K.H., 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, Florida, USA.
- Nastev, M., 1998. Modeling landfill gas generation and migration in sanitary landfills and geological formations. Ph.D. Thesis, LAVAL University.
- Ozakaya, B., A. Demir and M.B. Bilgili, 2006. Neural network prediction model for the methane fraction in biogas from field-scale landfill bioreactors. *Environ. Modeling Software*, 22: 815-822.
- Reinhart, R. and A. Faour, 2004. First-Order Kinetic Gas Generation Model Parameters for Wet Landfills. University of Central Florida, USA.
- SWANA, 1998. Comparison of Models for Predicting Landfill Methane Recovery. Publication No. GR-LG 0075, The Solid Waste Association of North America, Dallas, TX.
- Sabour, M. and H. Kamalan, 2006. Energy element (Methane) recovery from municipal solid waste treatment facilities. Proceedings of the Biomass and Waste to Energy Symposium, Nov. 29-Dec. 1, Venice, Italy, pp: 12-12.
- Sabour, M.R., A. Mohamedifard and H. Kamalan, 2007. A mathematical model to predict the composition and generation of hospital wastes in Iran. *Waste Manage.*, 27: 584-587.
- Scharff, H. and J. Jacobs, 2006. Applying guidance for methane emission estimation for landfills. *Waste Manage.*, 26: 417-429.

- Scheepers, M.J.J. and B. van Zanten, 1994. Handleiding Stortgaswinning. Adviescentrum Stortgas, Utrecht, Netherlands, (In Dutch).
- Shariatmadari, N., M. Sabour, H. Kamalan, A. Mansouri and M. Ablofazlzade, 2007. Applying simple numerical model to predict methane emission from landfill. *J. Applied Sci.*, 7: 1511-1515.
- Steger, A.G. and D.L. Murray, 2003. User's Manual Mexico Landfill Gas Model. EPA., Washington.
- Thorneloe, S.A., A. Reisdorph, M. Laur, R. Pelt, R.L. Bass and C. Burklin, 1999. The U.S. environmental protection agency's landfill gas emissions model (LandGEM). Proceedings of Sardinia 99 Sixth International Landfill Symposium, Volume IV Environmental Impact, (SILSVEI'99), Aftercare and Remediation of Landfills, pp: 11-18.
- Van Heut, R.E., 1986. Estimating landfill gas yields. Proceedings GRCDA 9th International Landfill Gas Symposium, (GILS'86), Newport Beach, California, pp: 92-120.