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RESEARCH ARTICLE

Modeling and simulation of landfill gas production from pretreated MSW landfill simulator

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Abstract The cumulative landfill gas (LFG) production and its rate were simulated for pretreated municipal solid waste (MSW) landfill using four models namely first order exponential model, modified Gompertz model, single component combined growth and decay model and Gaussian function. Considering the behavior of the pretreated MSW landfill, a new multi component model was based on biochemical processes that occurring in landfilled pretreated MSW. The model was developed on the basis of single component combined growth and decay model using an anaerobic landfill simulator reactor which treats the pretreated MSW. It includes three components of the degradation i.e. quickly degradable, moderately degradable and slowly degradable. Moreover, the developed model was statistically analyzed for its goodness of fit. The results show that the multi components LFG production model is more suitable in comparison to the simulated models and can efficiently be used as a modeling tool for pretreated MSW landfills. The proposed model is likely to give assistance in sizing of LFG collection system, generates speedy results at lower cost, improves cost-benefit analysis and decreases LFG project risk. It also indicates the stabilization of the landfill and helps the managers in the reuse of the landfill space. The proposed model is limited to aerobically pretreated MSW landfill and also requires the values of delay times in LFG productions from moderately and slowly degradable fractions of pretreated MSW.

Keywords combine growth and decay model, pretreated municipal solid waste (MSW), multi component landfill gas (LFG) model

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1 Introduction

Landfilling is one of the most commonly adopted technologies for municipal solid waste (MSW) disposal as an alternative to waste burning and composting. In most of the western countries over the past few years, MSW landfilling has been significantly developed. These landfills decrease the environmental consequences caused by the unsanitary landfills and open dumps [1]. MSW has different organic and inorganic fractions. Leachate and biogas are two pollutants which are emitting from MSW landfills [2]. The production of landfill gas (LFG) and leachate are still unavoidable disadvantages, though the landfill technology has been improved from open dump sites to engineered sanitary landfill. These environmental consequences of these sanitary landfill sites can be addressed by using different tools of landfill management like mathematical modeling. Mathematical modeling is helpful in estimation of quality and quantity of LFG and leachate. Anaerobic degradation of the organic material results in formation of LFG, which is the combination of carbon dioxide (CO_2), methane (CH_4) and small quantities of other gases. Modeling of the LFG is an exercise of estimation of gas production its retrieval and its retrieval efficiency [3].

If LFG emissions are beyond control, it is significant hazard to the environment [4]. CH_4 and CO_2 are the two gases which are primarily accountable for global warming [5]. Though, CH_4 concentration in the atmosphere is lower than that of CO_2, but it is 21–25 times more powerful greenhouse gas than CO_2 [6]. Biogenic processes are the main sources of the release of the CH_4 and CO_2 [7]. The substantial source of production of CH_4 is the MSW landfills, which accounts about 12% to 18% of yearly worldwide anthropogenic CH_4 productions [8]. Numerous attempts have been made to make the sanitary landfills stable; one of them was the pretreatment of volatile solids (VS) from mixed un-shredded MSW through natural air convection before landfilling [9,10]. Employing aerobic pretreatment (natural air convection) can significantly decrease the lag phase time of the LFG production by 74.1% to 97.0%. This aerobic treatment eventually converts VS present in the MSW into CO_2 rather than into unrestrained LFG and extremely polluted leachate [11].

The path of conversion VS to LFG is somewhat assumed comparable to that of for anaerobic digestion process. The VS is transformed to biogas through a sequence of interconnected bacteriological breakdowns. The anaerobic digestion process broadly includes three stages that are hydrolysis, acetogenesis, and methanogenesis [12]. The LFG production model approaches the landfill as batch reactor [2]. The kinetics of the anaerobic digestion is assumed as first order with respect to biodegradable material. Moreover, the accumulation of biogas in the landfill is considered as negligible. As the solid waste is placed in the landfill site, it will breakdown through chemical and bacterial activities. Primarily, the solid waste experiences the process of hydrolysis in which proteins, carbohydrates and fats are decreased to soluble compounds. In the subsequent stage the hydrolyzed material is converted into the organic acids, which are again breakdown into acetic acid. Methanogenesis is the last stage, where acetic acid is converted to CH_4 and CO_2 while, hydrogen (H_2) and CO_2 react to produce CH_4 [13].

LFG model is a tool to project LFG production over the incubation time from a certain mass of waste that has to be landfilled. The model gives assistance in sizing of LFG collection system, forecasting of LFG production potentials and their efficient utilization. Moreover, in response to regulatory necessities beneath the Clean Air Act (CAA), LFG production model helps in installation of LFG collection and treatment mechanisms. The other advantages of the LFG models include lower cost and speedy results of the LFG production and other related parameters, improved cost-benefit analysis and decreased LFG project risk. The LFG production model also indicates the stabilization of the landfill and helps to the managers in the reuse of the landfill space. In past, many models were developed to demonstrate LFG production from sanitary landfills including modified Gompertz model which is based on bacteriological development curve, the model based on bio-kinetic characteristics [14,15] and the model based on environmental features [16]. A landfill is very compound mixed surrounding environment and face up several modeling challenges. Landfilled MSW undergoes degradation through complex biological and chemical processes. At the start of landfilling, VS follows aerobic degradation, but by the time as the quantity of the waste increases layer by layer it follows anaerobic degradation. Thus, landfills bear a resemblance to that of an anaerobic digester. All the models employed for prediction of the LFG throughout the world are based on first order decay (FOD) model, in which depletion of VS in the landfilled waste with respect to the time is taken into account [17]. Moreover, all FODs have linear relation with ultimate production of methane per unit mass of landfilled waste and have an exponential relation with rate of degradation and time of incubation. The simplest FOD model is represented in Eq. 1 [18].

$$G = m \times L_0 \times e^{-k(t-t_1)}, \quad (1)$$

where G is LFG production in $m^3 \cdot year^{-1}$; m is mass of landfilled waste in tons; L_0 is LFG yield potential in $m^3 \cdot ton^{-1}$ of landfilled waste; t is time after waste placement in year; t_1 is lag phase time and k is first order rate constant in $year^{-1}$. Another FOD model is TNO model as represented in Eq. 2 [19].

$$G = 1.87 \times \zeta \times m \times C_0 \times k \times e^{-kt}, \quad (2)$$

where G is LFG production in $m^3 \cdot year^{-1}$; 1.87 is the conversion factor having dimension as $m^3 \cdot kg^{-1}$ (biodegradation of the one kg of organic carbon that is landfilled produces 1.87 Nm^3 of LFG); ζ is the formation factor (certain fraction landfilled waste that is converted into LFG); m is mass of landfilled waste in ton; C_0 is the amount of degradable organic carbon in $kg \cdot ton^{-1}$ of landfilled waste; t is time after waste placement in year and k is first order rate constant in $year^{-1}$. Both the models stated above are based on one component degradation of MSW in the landfill and lack the multi components approach, which introduces gross oversimplification. Moreover, both the models have only one exponentially decreasing LFG production curve.

Afvalzorg model is a three component model for estimation of LFG production and it seems to be similar to TNO model as stated in Eq. 2, with some modification and is employed for the mixed solid waste having eight different waste types. This model also considers three fractions of waste i.e. rapid, moderate and slow degradable as given in Eq. 3 [19].

$$G = 1.87 \times \zeta \times m \times \sum_{i=1}^{3} C_{0,i} \times k_i \times e^{-k_i t}, \quad (3)$$

Where i represent the degradation fraction of the landfilled waste and have values from 1 to 3 for rapid, moderate and slow waste fractions. In this model the LFG production has three curves, which decreases exponentially and does not have any rising limb, it is not suitable for LFG production rates.

All the LFG models reported in Eqs.(1-3) are for untreated MSW landfills, while a little literature is available on the LFG models for pretreated MSW landfills. The objective of this study was to simulate the cumulative LFG production and LFG production rate for pretreated MSW landfill by means of four models i.e. first order exponential model, modified Gompertz model, single component combined growth and decay model and Gaussian function and to propose a new mathematical model for the prediction of methane production rate. The results of proposed model were compared with the above models and two components model available in literature. For this purpose, anaerobic landfill simulator reactor (ALSR) was developed with controlled temperature with leachate recycling mechanism. ALSR was fed with pretreated MSW and LFG production was measured. The MSW was pretreated aerobically by natural convection of air as described in earlier study [20]. Pretreatment of the MSW decreases some quantity of degradable material and thus remaining residue was landfilled.

2 Methodology

2.1 Composition of MSW

The sample of MSW was picked from Beijing's Beishenshu landfill site. Its nature was mixed and comprising 60% of VS. The collected sample was segregated manually and its composition was determined as shown in Fig. 1.

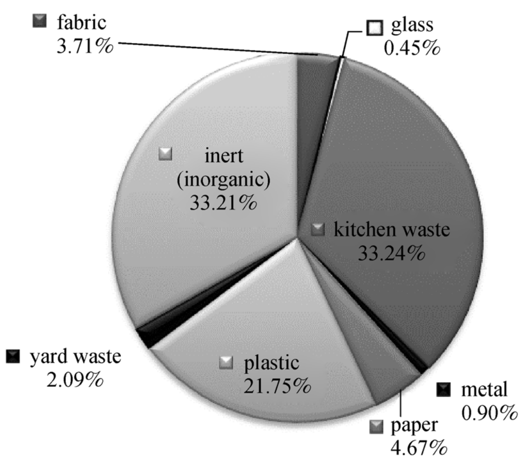

Fig. 1 Composition of untreated MSW of Beishenshu landfill Beijing, China (% TS)

2.2 Characteristics of pretreated MSW

After five months of aerobic treatment by natural convection in aerobic pretreatment simulator (APS), nine pretreated MSW samples were taken from three random points of the APS. From each point, three samples were taken from top, mid and bottom of the height of the APS. The nine pretreated MSW samples were then dried in air atmospheric temperature and then chopped to have a size of less than 20 mm in diameter and were made uniform in terms of composition, which made sure that the sample taken for the analysis and to be landfilled was representative.

The moisture content and VS in pretreated MSW sample were determined according to standard method [21]. The percentages of elemental hydrogen, carbon, and nitrogen were determined by flash combustion method in elemental analyzer (EAI, USA). The gravimetric method was employed to determine the percentage lignocellulose material [22]. Bulk density was measured by filling pretreated MSW sample in cylinder and weighing cylinder before and after sample filling. Bulk density was calculated by dividing mass of pretreated MSW sample to volume it occupied. The pH of pretreated MSW was measured through a hydrogen ion sensitive electrode by preparing its slurry with the distilled water. SCOD was measured for filtered sample according to standard method [21]. The characteristics of pretreated MSW are given in Table 1.

2.3 Anaerobic landfill simulation reactor

The laboratory scale anaerobic landfill simulation reactor (ALSR) was established with an aim to study the behavior of pretreated MSW in the landfill. The sectional view of ALSR assembly is shown in Fig. 2. It comprises of two shells. The inner shell was air tight having capacity of about 25 liters (0.3 m diameter and 0.35 m height). The bottom of the inner shell was filled with a 25 mm layer of gravel followed by a membrane. The leachate was collected through leachate collection hopper. The top of the inner shell was provided with water diverting mechanism containing 25% NaCl solution for volumetric measurement of LFG and the rain water sump along with membrane for rain water simulation. The temperature of the inner shell was controlled by the water; filled in the outer shell at 40±1°C by using heating element, which is linked with temperature controller as shown in Fig. 2. By quartering about 10 kg sample, the ALSR was filled with pretreated MSW and of the identical volume of water was added followed by properly mixing. It was operated for more than one year and the LFG production during this period was measured. The tap water was also added to the ALSR as a rainfall simulation. The tap water was added at the rate of 3.5 mm fortnightly.

2.4 LFG production simulation

Cumulative LFG production was simulated using two

Table 1 Characteristics of pretreated MSW by natural convection of air

parameters	moisture content/ %	VS / (%TS)	carbon / (%TS)	hydrogen / (%TS)	nitrogen /(%TS)	lignocellulose /(%TS)	bulk density / ($kg\cdot m^{-3}$)	pH	SCOD / ($mg\cdot L^{-1}$)
pretreated waste	21±1	26.39±0.54	15±0.62	1.61±0.2	0.76±0.21	18±0.7	520±3	5.7±0.1	1773±15

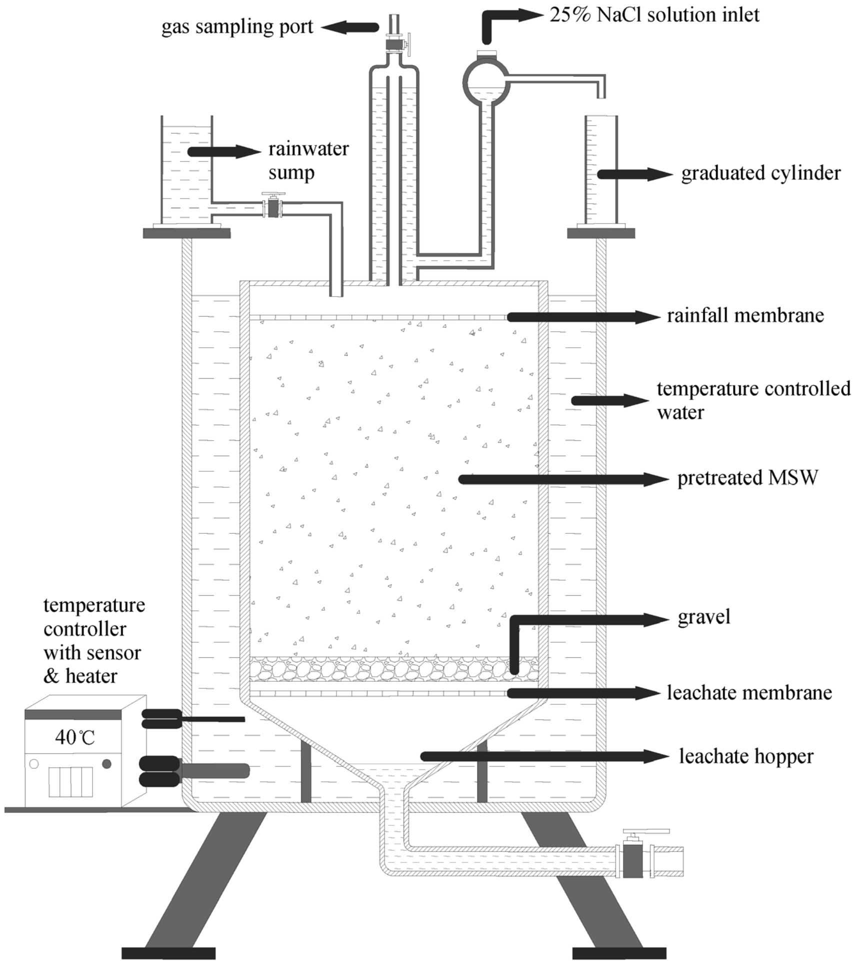

Fig. 2 Sectional view of ALSR

models i.e. first order exponential model and modified Gompertz model. Because of the bacteriological involvement in the anaerobic digestion process, the first order exponential model has been commonly employed to simulate the anaerobic biodegradation in the landfills [23,24]. First order exponential model for cumulative LFG production from pretreated MSW is presented in Eq. 4.

$$LFG = LFG_u(1-e^{-kt}), \tag{4}$$

where, LFG is the cumulative LFG production in $m^3 \cdot ton^{-1}$ MSW(DM), t is the time on day over the digestion period. LFG_u is the LFG production potential in $m^3 \cdot ton^{-1}$ MSW (DM) and k is the first order kinetic constant day^{-1}. The LFG_u and k were estimated analytically through non–linear regression using least square method. Modified Gompertz model was another commonly used model for simulation of cumulative LFG production [25,26]. The modified Gompertz model for cumulative LFG production from pretreated MSW is given in Eq. 5.

$$LFG = LFG_u.\exp\left[-\exp\left\{\frac{R_m.e}{P}(\lambda-t)+1\right\}\right], \tag{5}$$

Where, LFG is the cumulative LFG production in $m^3 \cdot ton^{-1}$ MSW(DM), t is the time in day over the digestion period, LFG_u is the LFG production potential in $m^3 \cdot ton^{-1}$ MSW (DM), R_m is the LFG production rate in $m^3 \cdot ton^{-1}$ MSW (DM)$\cdot day^{-1}$, λ is the lag-phase time in day, and e is the exponential of 1. The LFG_u,R_m and λ were estimated analytically through non–linear regression using least square method.

In addition to the cumulative LFG production, LFG production rates of pretreated MSW were also simulated using combined growth and decay model as defined by Zachrarof & Butler [3] and Gaussian function. The combined growth and decay model for cumulative LFG production from pretreated MSW is given in Eq. 6.

$$LFG(t) = Ate^{-kt}, \tag{6}$$

Where LFG (t) is the LFG production rate in $m^3 \cdot ton^{-1}$ MSW(DM)$\cdot day^{-1}$ at time t in day, t is the time over the digestion period, A is the amplitude in $m^3 \cdot ton^{-1}$ MSW (DM)$\cdot day^{-2}$) and k is reaction rate constant in day^{-1}. The A and k were estimated analytically through non–linear regression using least square method.

Gaussian model was another model used for simulation of LFG production rates from pretreated MSW [24], which assumes that the LFG production rate follow the normal distribution. Gaussian model can be employed to simulate LFG production rates including climbing and descendent member and is presented in Eq. 7.

$$LFG(t) = ae^{\left[-0.5\left(\frac{t-t_0}{b}\right)^2\right]}, \quad (7)$$

Where, $LFG(t)$ is the LFG production rate in $m^3 \cdot ton^{-1}$ MSW(DM)$\cdot day^{-1}$ at time t in day, t is the time over the digestion period, a is the ultimate LFG production rate in $m^3 \cdot ton^{-1}$ MSW(DM)$\cdot day^{-1}$ and b is constant in day and t_0 is the time in day where the peak (maximal) LFG production rate occurred. The parameters a, b and t_0 were estimated analytically through non–linear regression using least square method.

2.5 Development of LFG production model

The mathematical representation of the LFG production rate follows one of the three approaches. In the first approach, the LFG production rate is represented as single/multiple empirical functions of a general kinetic factor which mostly appears in the literature [27–29]. The second approach includes the representation of the LFG production rate in a complex sum of mathematical functions, which are based on the physical, chemical and biological processes of biodegradation and variables including moisture content, operating temperature, elemental composition, volatilization, dilution, precipitation, oxidation, evaporation, reduction, adsorption, absorption, filtration, complexion and neutralization. To determine these characteristics inside the landfill, a significant amount of detailed analysis is required. The complex mathematical model available in literature for landfilled waste is Halvadakis model [14], which is first order model and is based on the consecutive biological growth. The third approach includes the models that consider LFG production rate in digits and are called numerical models. The numerical models are robust in estimation of production of LFG, if all the phenomena takes place within the degradation of landfilled waste are known [18]. The most concerned variable in landfill modeling is time as the anaerobic degradation of the MSW extremely depends on time. If the combined growth and decay rates are defined as functions of time, then there will be dual advantage. The foremost advantage is related to the digestion of waste as it is more readily understood and on second unrepresentative use of biomass concentration is avoided. This will not only simplify the structure of the model, but it will also improve model's functionality for which it is developed. The proposed model was constructed as multiple empirical functions having multiple kinetic factors and was based on the combined growth and decay function as defined by Zachrarof and Butler [3] in the following form:

$$R(t) = Ate^{-kt}, \quad (8)$$

Where, $R(t)$, is the rate of reaction at time t in $kg \cdot year^{-1}$; A is an amplitude term in $kg \cdot year^{-2}$ and k, is rate constant in $year^{-1}$. The rate of reaction is an illustration of the outcome seen in bacteriological development and it requires only two values that are an amplitude and rate constant. As shown in Fig. 3, the curve produced by using Eq. 8 increases abruptly, which represents fast growth and then after reaches at the highest point it follows an exponential decline to zero. This behavior is result of the hydrolysis stage of the anaerobic digestion. Furthermore, Zachrarof & Butler [3] suggested that the algorithm of the model in Eq. 8 can be enhanced by incorporating time variant fluxes. The MSW is heterogeneous in nature. It comprises of various types of biodegradable components and has different degradation rates. Thus in this study we propose the multi-components model as given in Eq. 9.

$$LFG(t) = \sum_{i=1}^{n}\sum_{j=0}^{m-1} A_{j+1}(t_i - t_j)e^{[-k_{j+1}(t_i - t_j)]}, \quad (9)$$

where LFG (t) is the LFG production at time t, in $m^3 \cdot ton^{-1}$ MSW(DM)$\cdot day^{-1}$; A is the amplitude in $m^3 \cdot ton^{-1}$MSW (DM)$\cdot day^{-2}$; k is the LFG reaction rate constant in day^{-1}; n is total number of days; m is number of biodegradable components of heterogeneous pretreated MSW. Moreover, $i \neq j$ and t_j is the delayed time, which is defined as period between the beginning times to the end of biodegradable components.

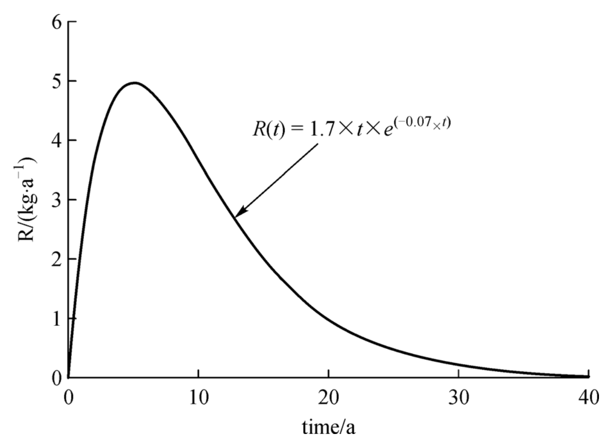

Fig. 3 Combined growth and decay function (A = 1.7 $kg \cdot day^{-2}$ and k = 0.07 $year^{-1}$)

Analyzing the LFG production data, obtained from ALSR, it was observed that the pretreated MSW may have three types of the biodegradable components i.e. m = 3; and are considered as quickly degradable, moderately degradable and slowly degradable components. Considering three degradable components Eq. 9 was expanded as

Eqs.(10 – 12):

$$LFG(t) = A_1 te(-k_1 t),\text{at } j = 0 \text{ and } t<t_1 \quad (10)$$

$$LFG(t) = A_1 te^{[-k_1 t]} + A_2(t-t_1)e^{[-k_2(t-t_1)]},\text{at } j = 1 \text{ and } t_1<t<t_2 \quad (11)$$

$$LFG(t) = A_1 te^{[-k_1 t]} + A_2(t-t_1)e^{[-k_2(t-t_1)]} + A_3(t-t_2)e^{[-k_3(t-t_2)]},\text{at } j = 2 \text{ and } t > t_2 \quad (12)$$

where:

$LFG\ (t)$ = LFG production in $m^3 \cdot ton^{-1}$ MSW(DM) $\cdot day^{-1}$;

A_1,A_2 & A_3 = Amplitudes in $m^3 \cdot ton^{-1}$ MSW(DM)$\cdot day^{-2}$ for quickly, moderately and slowly degradable matters;

t_1 & t_2 = delayed time in day of LFG production between the fractions of the organic matters;

k_1, k_2 & k_3 = LFG reaction rate constant in day^{-1} for quickly, moderately and slowly biodegradable organics

The LFG production rate constants and amplitudes were estimated through non-linear regression using least square method from experimental data in MATLAB software. The non-linear regression was done in three steps, considering three components model i.e. Eqs.(10-12). The coefficients of each component of model are given in Table 2.

2.6 Validation of models

The newly developed multi components LFG model and four models, used for simulation of the LFG production were corroborated by using two statistical parameters; namely coefficient of determination (R^2) and root mean square error (*RMSE*). These parameters are comprehensive to quantify the accuracy of the proposed model. R^2 was calculated by Eq. 13. It represents the association between experimental LFG (LFG_{exp}) and modeled LFG (LFG_{mod}) at time *i* for *n* number of days. The model with a greater value of R^2 establishes the better predicting.

$$R^2 = 1 - \frac{\sum_{i=1}^{n} \left(LFG_{\text{exp},i} - LFG_{\text{mod},i}\right)^2}{\sum_{i=1}^{n} \left(LFG_{\text{exp},i} - \overline{LFG_{\text{mod},i}}\right)^2}. \quad (13)$$

The *RMSE* is a measure of the mean difference between predicted and experimentally observed values. It was calculated by using Eq. 14.

$$RSME = \sqrt{\frac{\sum_{i=1}^{n} \left(LFG_{\text{exp},i} - LFG_{\text{mod},i}\right)^2}{n}}. \quad (14)$$

3 Results and discussion

3.1 Cumulative LFG production and its rate

The cumulative LFG production for the period of 411 days from the ALSR and its flow rate are shown in Fig. 4. Heyer and Stegmann [30] described that in conventional landfill, there are various stages of decomposition of MSW. The first short duration stage is aerobic in that oxygen is spent and nitrate is formed in leachate; whereas other stages are anaerobic. In case of pretreated MSW, the first stage was diminished and only anaerobic components were observed as LFG production started by first day of incubation. The peak LFG production rate was observed on 55th day of incubation as 3.09 $m^3 \cdot ton^{-1}$ MSW(DM)$\cdot day^{-1}$ and it decreased to almost zero at 275 days.

3.2 Simulation and modeling

Regarding cumulative LFG production simulation, mod-

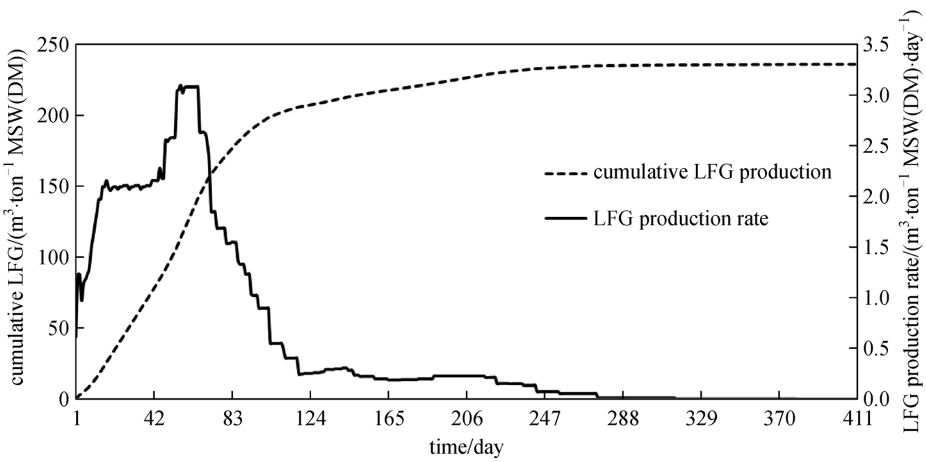

Fig. 4 Cumulative LFG and its production rate through ALSR

ified Gompertz model showed better R^2 of 0.995 than first order exponential model of 0.972 as shown in Fig. 5 (a and b). A similar trend was observed in the values of *RMSE* that the modified Gompertz model evidenced better fit and had lower RMSE of only 1.477 $m^3 \cdot ton^{-1}$ MSW(DM) in comparison to the RMSE of 10.52 $m^3 \cdot ton^{-1}$ MSW(DM) for first order exponential model.

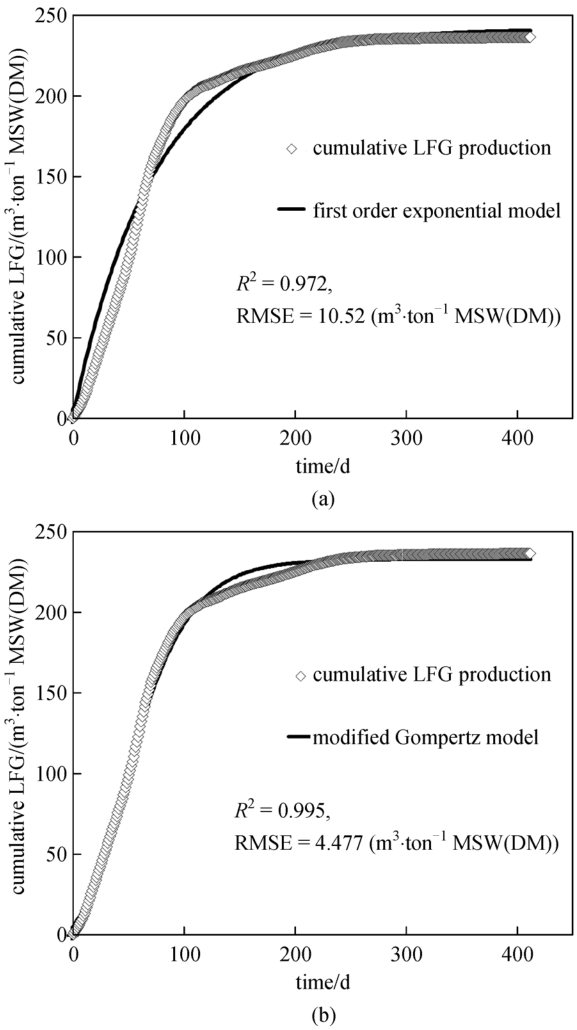

Fig. 5 Cumulative LFG production (a) first order exponential model and (b) modified Gompertz model

Considering LFG production rate simulation, Gaussian function showed better R^2 of 0.954 than single component combined growth and decay model of 0.912 as depicted in Fig. 6 (a and b). A similar fashion was observed in the values of *RMSE* that the Gaussian function demonstrated better fit and had lower *RMSE* of only 0.185 $m^3 \cdot ton^{-1}$MSW(DM)$\cdot day^{-1}$ in comparison to the *RMSE* of 0.256 $m^3 \cdot ton^{-1}$MSW(DM)$\cdot day^{-1}$ for single component combined growth and decay model.

The single component combined growth and decay

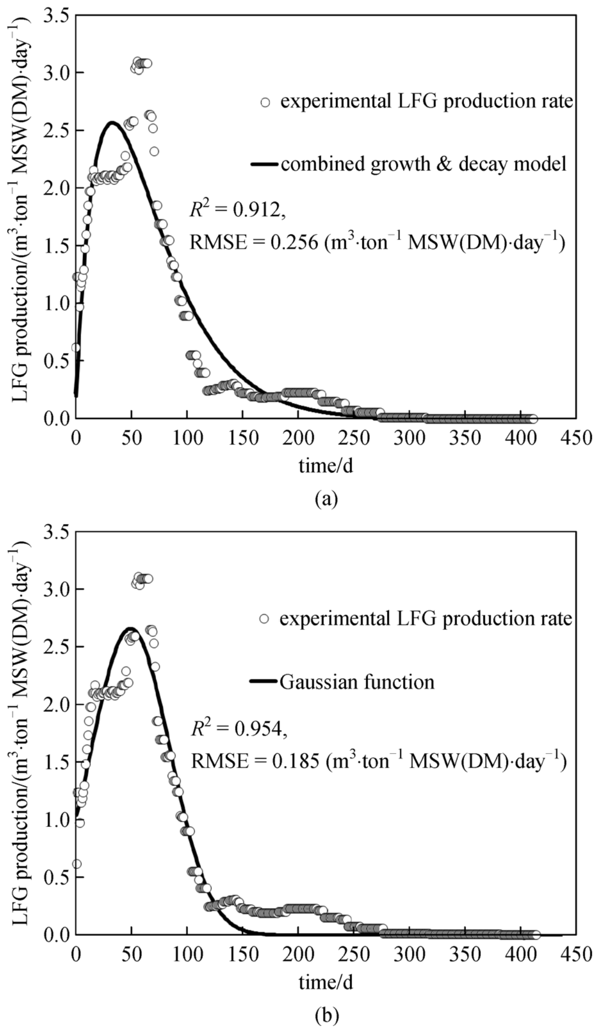

Fig. 6 LFG production rate (a) combined growth and decay model and (b) Gaussian function

model and Gaussian function were fitted to experimental data and observed that Gaussian function is better fit than former one. This is because of considering only one type of material in the present study (pretreated MSW). On the contrary, by considering the multi components of degradation of pretreated MSW (quickly degradable, moderately degradable and slowly degradable), it was found that the newly developed multi components combined growth and decay model had become more accurate than the Gaussian function.

The multi components combined growth and decay LFG production model along with experimental data was plotted as shown in Fig. 7. The delayed time of LFG production was taken from the experimental data trend of LFG production. For moderately and slowly degradable matters, delay time t_1 and t_2 were 15 and 50 days respectively. As the quickly and moderately degradable components were used up till LFG production rate reached

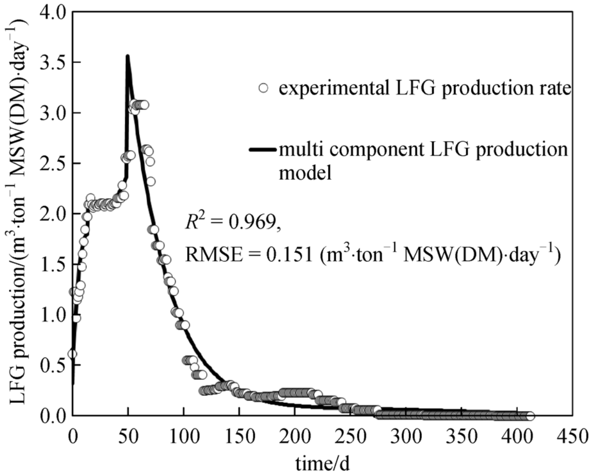

Fig. 7 Multi component combined growth and decay LFG production model versus experimental data

to peak then exponential decay followed to back zero. In comparison to single component combined growth and decay model and Gaussian function, the multi component LFG production model demonstrates better fit with R^2 value of 0.969 and *RSME* of only 0.151 $m^3 \cdot ton^{-1}$MSW (DM)$\cdot day^{-1}$. All these three models were compared statistically and it was observed that the multi-components model has better correlation with the experimental data and has 40% and 20% less *RMSE* as compared to the single component model and Gaussian function respectively.

In recent past, Gioannis et al. [23] has developed a two stage model, which is based on the first-order exponential model. The model was capable to predict LFG production rate for aerobically mechanical biological treated waste (MBTW) and the development of the LFG production rate was estimated for the three different ratios of waste. As per a two stage model, as the time passes the LFG production rate rises and is comparative to the volume of LFG that has been previously formed. Throughout the second stage, the LFG production rate is comparative to the remaining quantity of biodegradable material and it declines as the time passes. The values of the R^2 were in the range of 0.81 to 0.90 for the first and second stages respectively. In comparison to two stages model, based on first-order exponential model developed by Gioannis et al. [23], multi component model proposed in this study has higher value of R^2 (0.969), thus later predicts more accurate LFG production rates over earlier.

As the LFG production rates for each type of the degradable fraction of MSW is different, so the LFG production rate constants will also be different. The LFG production rate constants and amplitudes for single component combined growth and decay model and for multi component LFG production model parameters were estimated by using experimental data through MATLAB program and are given in the Table 2. The proposed model has some limitations that it is applicable to aerobically (natural convection of air) pretreated MSW landfill and it also requires the values of delay times in LFG productions from moderately and slowly degradable fractions of pretreated MSW.

4 Conclusions

On the subject of cumulative LFG production simulation, modified Gompertz model depicted better fit in comparison to the first order exponential model. On the other hand, regarding the LFG production rate, the newly developed multi-components mathematical model for LFG production, from anaerobic landfill simulator reactor, based on biochemical processes is more accurate in comparison to single component combined growth and decay model and Gaussian function. All these three models were compared statistically and it was observed that multi-components model has better fit with experimental data and has 40% less RMSE as compare to the single component model. Correspondingly, multi-components model has about 20% less RMSE as compare to the Gaussian function. Thus, it is concluded that the multi component LFG production model provides better fit in comparison to the simulated models and was well described by a three components. Additionally, un-shredded aerobically pretreated MSW includes three components of the degradation of the pretreated MSW i.e. quickly degradable, moderately degradable and slowly degradable. The proposed model can efficiently be used as modeling tool for pretreated MSW landfills.

Table 2 Model parameters and statistical analysis of LFG production models of pretreated MSW

combined growth and decay model	Eq.	amplitude/($m^3 \cdot ton^{-1}$MSW(DM)$\cdot day^{-2}$)			rate constant/(day^{-1})			R^2	*RMSE* /($m^3 \cdot ton^{-1}$MSW(DM)$\cdot day^{-1}$)
		A_1	A_2	A_3	k_1	k_2	k_3		
single component	(9)	0.2066	–	–	0.0296	–	–	0.912	0.255
multi components	(10)	0.3414	–	–	0.0699	–	–	0.969	0.151
	(11)	0.1400	−0.1625	–	−0.0016	0.0026	–		
	(12)	0.1035	0.0538	−0.1223	0.0150	0.0150	0.0165		

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