Linguistic modeling of biogas generation in simulated anaerobic bioreactor landfills

Mohamed S. Abdallah
Department of Civil Engineering - University of Ottawa, Ottawa, ON, Canada
Mostafa A. Warith
Department of Civil Engineering - Ryerson University, Toronto, ON, Canada
Leta Fernandes & Septa Rendra
Department of Civil Engineering - University of Ottawa, Ottawa, ON, Canada

ABSTRACT
A fuzzy linguistic model was developed to simulate the effect of leachate recirculation and sludge addition on the biogas generation in anaerobic bioreactor landfills. The model was designed using a fuzzy logic system which incorporated 3 input variables (time, leachate recirculation, and sludge addition) and a single manipulated output (biogas generation rate). The experimental work involved the operation of simulated lab-scale bioreactors for over a year with various operating schemes. The model was verified and validated against measured data which was compiled from the present experiment as well as earlier published studies.

RÉSUMÉ
Un modèle de logique floue a été développé pour simuler les effets de la recirculation du lixiviat et de l'ajout de boues activées sur la génération de biogaz dans les bioréacteurs anaérobie enfouis. Le modèle comporte trois variables d'entrées (le temps, la recirculation du lixiviat, et l'addition de boues) et une variable de sortie calculée (le taux de génération de biogaz). Le travail expérimental a consisté en l'opération pendant plus d'un an de modèles réduits de bioréacteurs à l'échelle du laboratoire avec divers modes opératoires. Le modèle a été vérifié et validé avec les données mesurées au cours de l'expérience ainsi que de données compilées à partir de la littérature.

1 INTRODUCTION

Leachate recirculation and sludge addition are among the most effective techniques used in enhancing the design and operation of bioreactor landfills. In both methods, the purpose is to control and manipulate the influencing factors, specifically moisture content and nutrients, in a positive manner to accelerate the biodegradation of municipal solid waste (MSW). One specific advantage for leachate recirculation is lowering the treatment cost and environmental impacts of the high strength leachate as the organic component of the leachate is reduced by the active biological communities within the refuse mass.

Several studies have developed models to simulate the physical and biochemical processes occurring within the landfills according to physical characteristics, such as climate, refuse mass and age (Peer et al. 1992), biokinetic characteristics (Findikakis et al. 1998; El-Fadel et al. 1989), and environmental factors, such as moisture content, sulfate, and volatile solids (Gurijala et al. 1997). In addition to former mathematical models, stochastic modeling was also implemented (Zacharof and Butler, 2004). Thus far, most of these models are practically inapplicable as they are complicated and require extensive data inputs. Furthermore, the uncertainties of solid waste characteristics as well as the complex processes taking place within the landfill add up difficulty in assessing the effect of separate factors influencing the degradation of solid waste in bioreactor landfills. Therefore, this study objected a different approach which is based on linguistic modeling presented in the fuzzy logic. The fuzzy logic can offer advantages in dealing with systems that are complex, ill structured and are best described qualitatively (Ibrahim, 2004).

Fuzzy logic is a generalisation of Boolean logic implementing the concept of partial truth or uncertainty, so within the fuzzy set theory an element can have a gradual membership to different sets. The system behaviour is described by defining fuzzy sets, fuzzy rules or so called IF-THEN rules and applying a fuzzy inference scheme. The generation of a fuzzy logic model can be based both on experts' knowledge and experimental data.

In this study, the fuzzy logic system was employed to develop a MSW biodegradation model in terms of biogas generation. The time, leachate recirculation, and sludge addition were set as the controlled input variables and the biogas generation was the only manipulated output variable. The developed fuzzy logic model (FLM) was verified using experimental data some of which was already used in building the rule base of the fuzzy inference system. Furthermore, the model was validated by examining its predictions using other experimental studies that were obtained from the literature.

2 MATERIALS AND METHODS

2.1 Experimental Setup

The experimental setup consisted of six simulated anaerobic bioreactor landfill modules made from Plexiglas with dimensions of 150 mm diameter and 550 mm height. The schematic representation of the simulated bioreactor is shown in Figure 1. The bioreactors were operated with a leachate recirculation system each equipped with an outlet port at the bottom for leachate collection, as well as an inlet port to distribute the simulated rainfall and the recycled leachate.

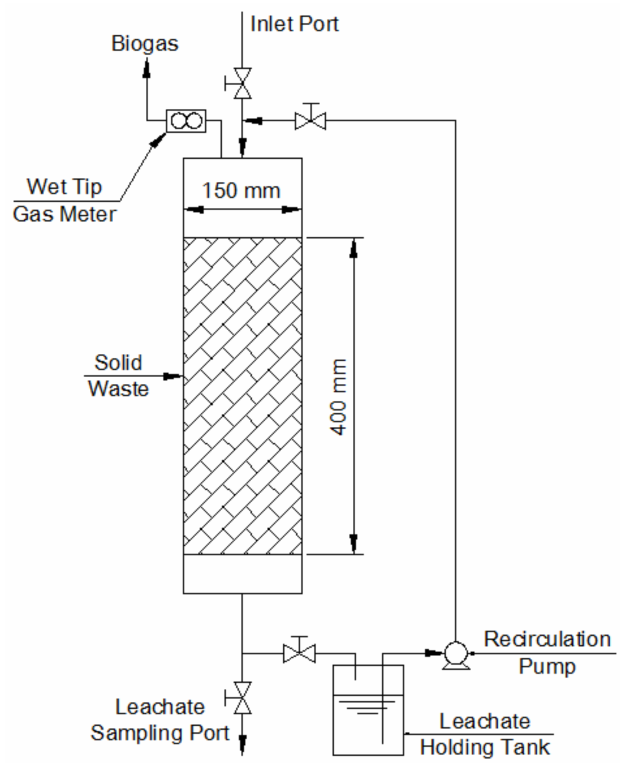

Figure 1. Configuration of the simulated anaerobic bioreactor

To achieve a representative sample of MSW commonly disposed in a landfill, waste was collected from the curbside of the city of Ottawa. The major components of this waste were paper (36.6%), food (36.2%), and yard trimmings (27.2%). The collected waste was shredded manually to a size of 50 to 100 mm and then mixed uniformly before being loaded into the bioreactors. The shredded solid waste was filled in 100 mm layers and compacted to a density of 350 kg/m3. The final height of the waste inside each bioreactor was 400 mm. The total mass and volume of waste in the bioreactors were 2.50 kg and 7 L, respectively.

The simulated rainfall was maintained at a rate of 2 L/wk. Leachate was recycled daily starting from the third week of operation. Anaerobically digested and thickened waste activated sludge from ROPEC Municipal Wastewater Treatment Plant in Ottawa were added to the bioreactors through the leachate recirculation system. The volume of gas produced in the simulated bioreactors was measured using a wet tip meter device. The number of tip readings were then converted into a rate of biogas generated using a calibration curve.

2.2 Operating Schemes

The operational arrangement of the six bioreactors is outlined in Table 1. The design strategy which was put forward for this study included four combinations of operating conditions and two center point replicates. The six reactors are characterized by R prefix.

Table 1. Operational conditions for the simulated bioreactors

Bioreactor	Rate of recirculation, ml/kg waste.d	
	Leachate	Sludge
R1	285	28.5
R2	855	28.5
R3	285	85.5
R4	855	85.5
R5	570	57.0
R6	570	57.0

2.3 Fuzzy Logic Controller

A static fuzzy logic controller (FLC) structure was designed to model the biodegradation of municipal solid waste. As illustrated in Figure 2, the main elements of the FLC structure include: (1) Inputs, (2) Fuzzification unit, (3) Data base, (4) Rule base, (5) Fuzzy inference engine, (6) Defuzzification unit, and (7) Outputs.

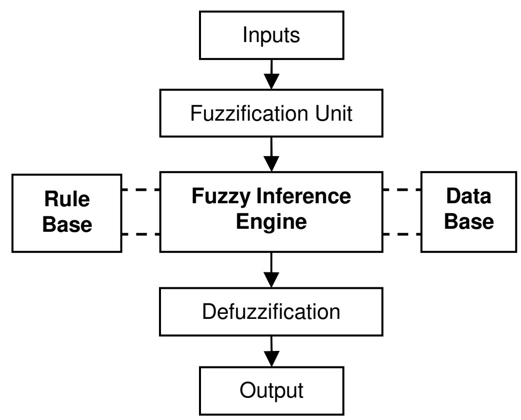

Figure 2 Structure of the Fuzzy Logic Controller

Inputs included time, leachate recirculation and sludge addition. The crisp values of the input variables were obtained from the conducted experimental work. The fuzzification is responsible for mapping the observed inputs to fuzzy sets in the universe of discourse. The fuzzification strategy involves the following: (a) acquiring the crisp values of the 3 input variables, (b) mapping the crisp values of the input variables into the corresponding universes of discourse, and finally (c) converting the mapped data into suitable linguistic terms so as to make it compatible fuzzy sets representation.

Data Base is provided by defining the membership functions of the fuzzy sets used as values for each system variable. Membership functions must be defined for each input and output variable. Any membership function, $\mu(x)$, is represented by a real number ranging between 0 and 1. Figure 3 illustrates the designed membership functions for the leachate recirculation and sludge addition as an example. The figure shows the fuzzy sets defined as Low Rate (LR), Medium Rate (MR) and High Rate (HR).

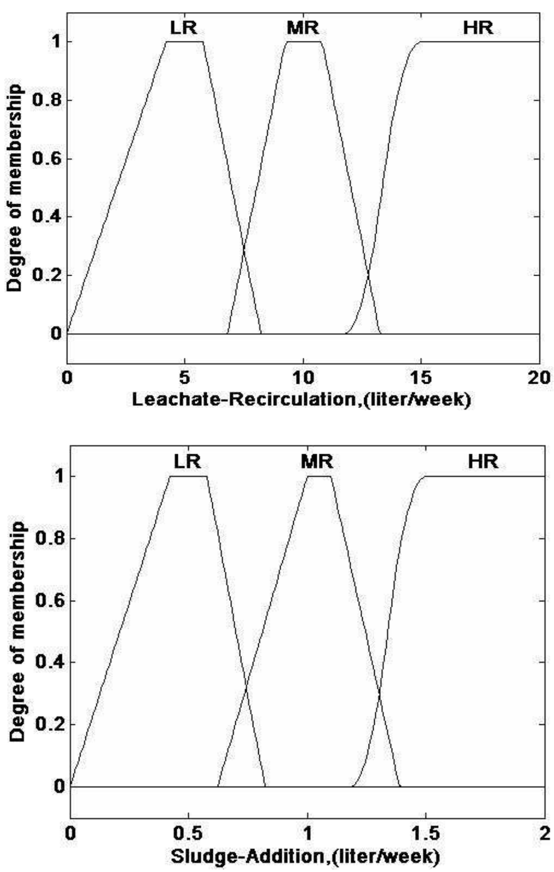

Figure 3 Membership functions of the operating variables

Rule base maps fuzzy values of the inputs to fuzzy values of the outputs. It consists of a number of fuzzy rules which define the system behavior. These rules are noted as IF–THEN statements that describe the action to be processed in response of various fuzzy inputs. A total number of 55 statements were used to describe the relations within the system variables precisely. The following rule is an example of the developed fuzzy rule base statements,

IF time is FS AND leachate recycling is HR AND sludge addition is HR, THEN biogas generation is MHR

where FS, HR and MHR, which denote the fussy sets of the input and output variables, stand respectively for full stabilization, high rate and medium high rate.

Fuzzy inference engine is required to determine the fuzzy output and to compute the rules along with the membership function of the fuzzy input. The MAX-MIN fuzzy inference technique was applied to compute a numerical value representing the aggregate effect of all that was triggered by an input value. The last step is the defuzzification which typically involves weighting and combining a number of fuzzy sets resulting from the fuzzy inference process in a calculation which gives a single crisp value for the output. The defuzzification method used in this study is the Centroid method. In this method, the defuzzified value, μ, can be calculated as:

$$\mu = \sum_{i=1}^{r} \mu_{C_i} \cdot c_i \Big/ \sum_{i=1}^{r} \mu_{C_i} \qquad [1]$$

where r is the total number of rules, μ_{C_i} is the degree of membership of the output fuzzy set i and C_i is the value associated with the peak of output fuzzy set i.

3 RESULTS & DISCUSSION

The main objective of the present work was to model the biodegradation process in anaerobic bioreactor landfills in terms of biogas production rate. The study focused on the effect of leachate recirculation and sludge addition as variable operating conditions on the biogas generation. The efficiency of the developed model is examined through both verification and validation. Initially, the model is verified by fitting its predictions adequacy to the present experimental data. Afterwards, the model is validated using earlier data that were published by San and Onay (2001) and Bae et al. (1998).

3.1 Model Verification

The general patterns of the biogas production in the six simulated bioreactors were apparently similar; starting with an increasing rate until a peak value, followed by declining phase and constant afterward. Figure 4 presents the model simulations and the experimental data of the biogas production rate for bioreactors R1, R2, and R6 as a sample of the present data set. The simulated results showed the model reliability in describing the progress of the data obtained during the experiment.

In R1, the model predictions were quite close to the experimental data, yet variations can be indicated. The differences of biogas production rate estimations were between 0.25 and 0.5 L/week. In R2, the simulation results were similar to the experimental data with the exception at the peak. Deviations of about 0.5 to 1.5 L/week are recognized from week 29 to 37 of the experiment.. Slight discrepancies between the predicted and measured biogas production rate occurred after week 29. In R6, the biogas production rate profile of the model simulation was similar and attached to the experimental data which indicated that the model developed was able to predict the actual data. From week 10 to 35, biogas production rate in the simulation results were about 0.5 L/week higher compared to the experimental data with the exception of week 19 to 23. Furthermore, from week 37 to 63, the predicted biogas production rate was about 0.25 L/week higher compared to the measured data.

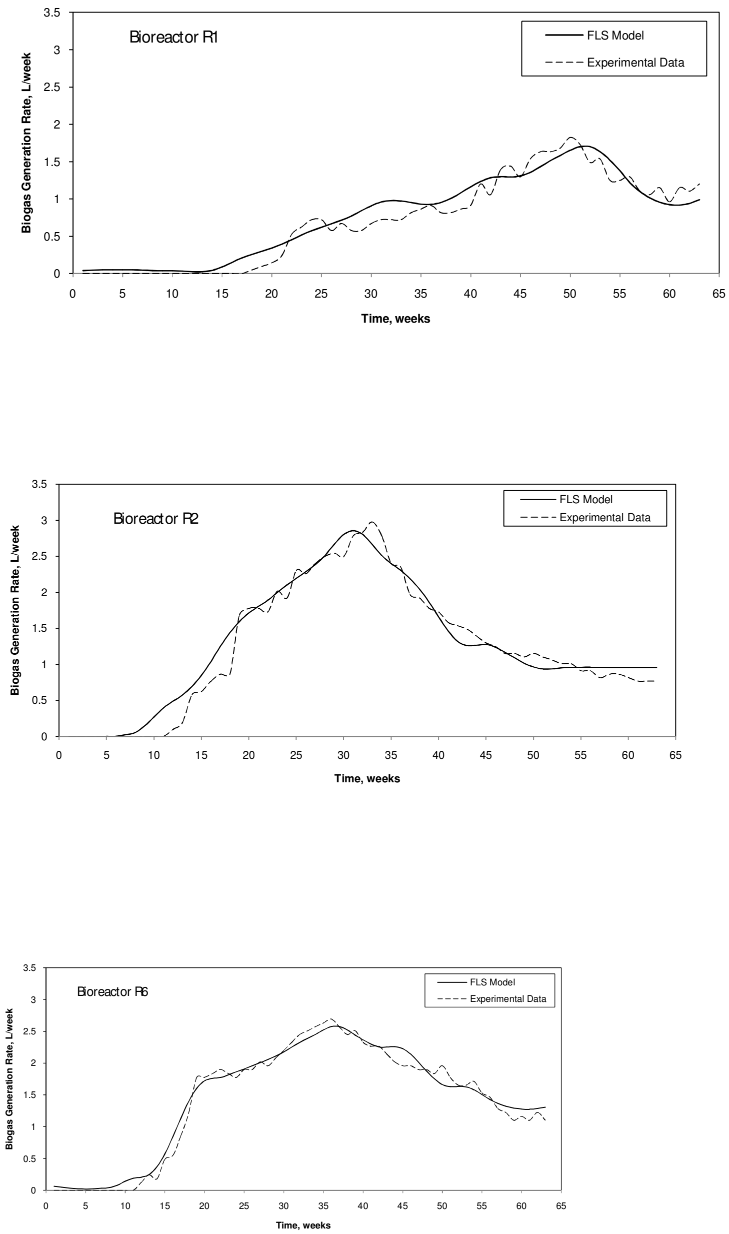

Figure 4 Measured and simulated biogas generation for bioreactors R1, R2, and R6

The correlation between the model simulations and the actual data was evaluated based on the linear regression between measured and simulated data. The developed model achieved ideal correlation coefficient (R) for all the bioreactors of around 0.98. Based on the previous discussion, the predictions of the FLM demonstrated reasonable agreement with the experimental observations, indicating the model capabilities and potentials in capturing the pertinent features of the solid waste biodegradation process.

3.2 Model Validation

Model validation is used to examine the applicability of the simulation model under different range of operating conditions. In selecting and developing a fuzzy model, one must consider the database availability to support and test the model. The validating data sets were compiled from the biogas generation results of two published studies on lab scale landfill bioreactors by San and Onay (2001) and Bae et al. (1998).

The first data set (San and Onay 2001) was obtained from lab-scale study. Two reactors simulating landfills, one with leachate recycle and the other without, were constructed with dimensions of 350 mm diameter and 1000 mm height. The reactor was filled with 13 kg of shredded and compacted synthetic solid waste. The average in-place density of solid waste in each reactor was 178 kg/m^3. The maximum volume of the recirculated leachate did not exceed 2 L. However, the recycling frequency was gradually increased from one to four times per week.

The second experimental study (Bae et al. 1998) was processed on lab-scale lysimeters where simulated rainfall and recycled leachate/sludge were added. Solid waste was collected at a transfer station that serves a residential area. For each lysimeter, 114 kg of solid wastes were filled at a density of 700 kg/m^3. Leachate was first treated by anaerobic digester, and then digester effluent was used for sludge addition.

The validation will be processed with the experimental data of the leachate recycled bioreactor and the sludge added bioreactor in the first and second experiments, respectively. Table 2 summarizes the main operating conditions for the selected experimental studies. The operational conditions and schedules were introduced to the FLM. The biogas generation rates from the model predictions are plotted together with the experimental data for the first and second experimental studies in Figures 5 and 6, respectively.

In the first experiment, the pattern of the biogas generation was irregular; the curve started with a major primary generation rate followed by gradual decrease to the dip. Then, the generation rate started to increase steadily until it reached the peak after 35 weeks when it finally started to drop down as theoretically expected. Generally, the model predicted the trend of the production pattern adequately despite the fact that it underestimated the generation rate during most of the operation period. The model simulations were fairly correlated to the actual data with a correlation coefficient (R) of 0.84.

In the second study, both the model simulations and the experimental data exhibited minor biogas generation at first, followed by a gradual increase to the peak, and then decrease until the end of the experiment. The model overestimated the biogas generation by an average percentage of 20% during the middle period of operation. In contrast, the model underestimated the peak and actually produced a constant generation rate during this period. Statistically, the correlation coefficient was high (R=0.91).

Even though deviations occurred between the experimental and predicted biogas generation rates, the overall model simulation proved significant concurrence with the experimental results. This validation states the potentials of the developed model in predicting biogas generation rates under various operational conditions.

Table 2 Main features and operating conditions of the studies used in validating the model

Study	Scale	Waste mass, kg	Type of recirculation	Range of recirculation rate, ml/kg waste.d
San and Onay (2001)	Lab	13	Leachate	11 – 88
Bae et al. (1998)	Lab	114	Sludge	0.7 – 1.32

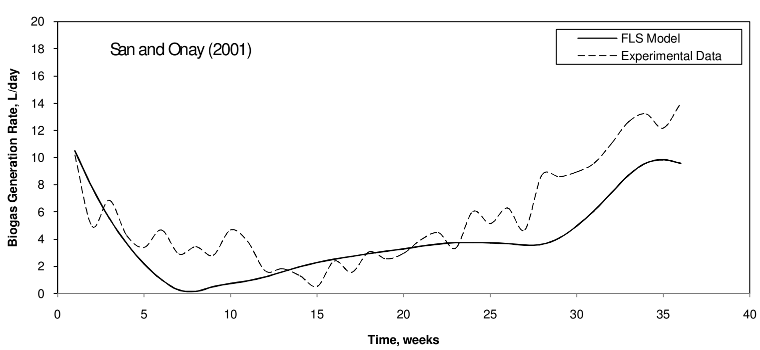

Figure 5 Measured and simulated biogas generation for San and Onay (2001)

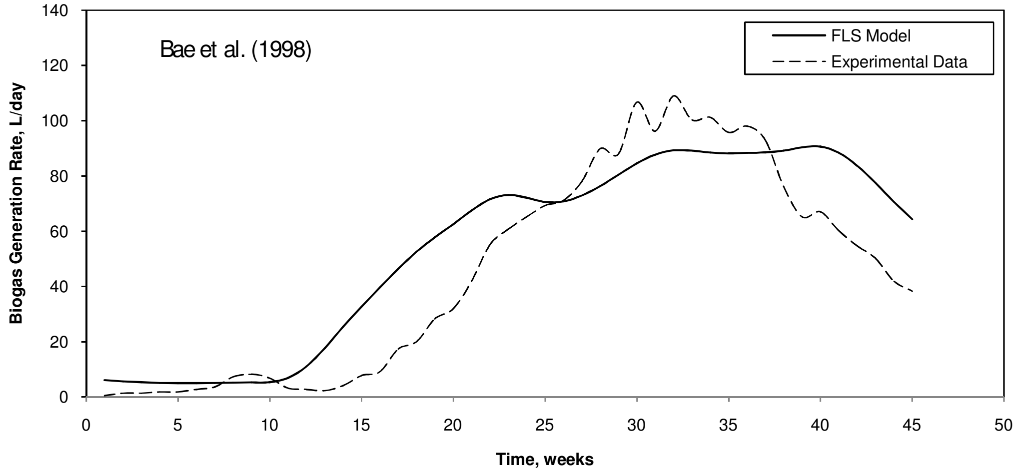

Figure 6 Measured and simulated biogas generation for Bae et al. (1998)

4 CONCLUSIONS

The fuzzy logic model simulation for biogas generation in anaerobic bioreactor landfills demonstrated reasonable agreement with the experimental observations. The FLM showed that the effect of leachate recirculation at the rate of (855 ml/kg waste.d) and sludge addition at the rate of (85.5 ml/kg waste.d) result in the highest biodegradation rate of municipal solid waste.

Although there were deviations between the model simulations and measured data, the simulation results can closely predict the trend of the process. The overall evaluation of the model confirmed its reliability to reproduce pertinent characteristics and important features of solid waste biodegradation under leachate recirculation and sludge addition. Generally, the application of the fuzzy logic system in modeling the solid waste biodegradation process can be considered as a successful simulating technique that implicitly describe the large number of complicated physical and biochemical reactions that occur within the landfills.

REFERENCES

Bae, J.H., Cho, K.W., Lee, S.I., Bum, B.S., and Yoon, B.H. 1998. Effects of Leachate Recycle and Anaerobic Digester Sludge Recycle on the Methane Production from Solid Wastes. Water Science and Technology, 38(2): 159-168.

El-Fadel, M., Findikakis, A.N., and Leckie, O.J. 1989. A Numerical Model for Methane Production in Managed Sanitary Landfills. Waste Management and Research, 7: 31-42.

Findikakis, A. N., Papelis, C., Halvadakis, C. P., and Leckie, J. O. (1988). Modeling Gas Production in Managed Sanitary Landfills. Waste Management and Research, 6: 115-123.

Gurijala, K.R., Sa, P., and Robinson, J.A. 1997. Statistical Modeling of Methane Production from Landfill Samples. Applied and Environmental Microbiology, 63(10), 3797-3803.

Ibrahim, A.M. (2004). Fuzzy Logic for Embedded System Applications. Elsevier Science Publisher, NY, USA.

Jang, R., Gulley, N. 1995. Fuzzy Logic Toolbox for Use with MATLAB. The MathWork Inc., USA.

Lay, J., Li, Y., and Noike, T. (1998). Mathematical Model for Methane Production from Landfill Bioreactor. Journal of Environmental Engineering, 124(8): 730-736.

Peer, R.L., Darcy, D.L., Campbell, D.L., and Brook, P.V. 1992. Development of an Empirical Model of Methane Emissions from Landfills. U.S. Environmental Protection Agency, Air and Energy Engineering Research Laboratory, EPA/600/SR-92/037.

San, I., and Onay, T. 2001. Impact of Various Leachate Recirculation Regimes on Municipal Solid Waste Degradation. Journal of Hazardous Materials B87: 259-271.

Sponza, D.T., and Agdag, O.N. 2004. Impact of Leachate Recirculation and Recirculation Volume on Stabilization of Municipal Solid Waste in Simulated Anaerobic Bioreactors. Process Biochemistry, 39: 2157-2165.

Rendra, S., Fernandes, L., and Warith, M. 2007. Fuzzy Logic Simulation of Biodegradation of Municipal Solid Waste in Simulated Aerobic and Anaerobic Bioreactors Landfill, 22nd International Conference on Solid Waste Technology and Management, Solid Waste Technology and Management, Philadelphia, USA.

White, J., Robinson, J., and Ren, Q. 2004. Modeling the Biochemical Degradation of Solid Waste in Landfill. Waste Management, 24: 227-240.

Zacharof, A.I., and Butler, A.P. 2004. Stochastic Modeling of Landfill Processes Incorporating Waste Heterogeneity and Data Uncertainty. Waste Management, 24: 241-250.