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Mathematical simulation and long-term monitoring of leachate components from two different landfill cells

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Abstract

In this study we monitored for 920 days the sulfate (SO_4^{2-}), chloride (Cl^-), chemical oxygen demand (COD) and biological oxygen demand (BOD) parameters in leachate produced in two large-scale test cells at the Odayeri Sanitary Landfill, Istanbul, Turkey. We present a mathematical model of these parameter concentrations in leachates of two test cells with one being the control (C1) and the other (C2) leachate recirculation. The relationship between these parameters and refuse age is simulated by a mathematical formula. The unknown constants of the simulation formula are solved by the least squares method, which minimizes the squared total of deviation from the model of the actual data using a MATLAB® computer program. A good fit was obtained between the measured data and model simulations. COD concentrations in leachate from C1 and C2 rapidly attained their maximum values of 75 and 70 g/l, respectively, after 1 month of landfilling. BOD to COD ratios are around 0.8 for both test cells during the acidogenic phase; this ratio then decreased to 0.06. A sharp decrease in the concentration of Cl^- from 14 to 15 g/l was observed after approximately 2 months of operation, followed by a slow decrease. SO_4^{2-} concentrations rapidly reached a maximum value of 2000 mg/l within 45 days; development of anaerobic conditions caused a sharp decrease to around 75 mg/l for C2 and 450 mg/l for C1 after 5 months of operation. The results showed that there appeared to be little improvement in leachate quality by leachate recirculation in terms of COD and BOD values, however, it is determined that the pollution loads more rapidly reached minimum values within the C2 test cell.

Keywords: Landfill; Leachate; Long term; MSW; Recirculation; Simulation

1. Introduction

A landfill site is a complex environment characterized by many interacting physical, chemical and biological processes. The degradation process of municipal solid waste (MSW) in a landfill is a long-term event. During MSW degradation, landfill gases are generated, the landfill surface settles and leachate concentrations are slowly and gradually attenuated [1]. Leachate concentrations may therefore exceed permissible levels over a long period of time. Hence, leachate is one of the most important issues in the management of a landfill.

Leachate recirculation is an inexpensive option for leachate management [2]. The moisture content of wastes is one of the most important factors that affect waste stabilization in landfills. Leachate recirculation reduces the time required for landfill stabilization from several decades to 2–3 years, thus minimizing the opportunity for long-term adverse environmental impact [3]. Many laboratory studies [4–6] and pilot-scale projects [7–10] have demonstrated that the rate and the extent of degradation of MSW can be enhanced beyond that observed in a conventional landfill by adding moisture or recirculating leachate. Leachate must be treated to achieve permissible standards after the pollution load of the treatment plant is minimized by recirculation. Chemical, anaerobic and aerobic processes are used for leachate treatment; these processes are complex and costs are usually high [1].

The concentrations and biodegradability of leachate decrease as the refuse age increases. In particular, the old leachate constituents distribute in a wide range of molecular weight fractions which for old leachates are found as complex structures formed by functional groups containing N (nitrogen), S (sulfur) and O (oxygen) atoms. The young leachate fractions have actually low molecular weights. The low molecular weight fractions of leachates are characterized by linear chains which are substi-

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tuted through oxygenated functional groups such as carboxyl and/or alcoholic [11]. Hence, the dependence of leachate concentrations on refuse age for the given landfill should be explored by considering effect of recirculation operation so that the reliable and accurate data can be provided for the optimization of leachate treatment processes.

Research on the composition of leachate, both in the laboratory [12] and in situ [13–15], has demonstrated a close relationship between climate, hydrology, origin, landfilling technology and operation. Ragle et al. [16] described large hourly and daily variations in the quality of leachate. Youcai et al. [1] and Khattabi et al. [17] reported a direct relationship between refuse age and type of leachate. Different model approaches have been used to understand the factors that influence landfill leachate quality and quantity [18–20].

The practice of leachate recirculation accelerates waste degradation via the provision of moisture, dilution of potential inhibitors to methanogenesis, and encouragement of water flux for microbial, substrate and nutrient transfer. This in turn facilitates the more rapid onset of methanogenic conditions and, hence, more rapid waste stabilization, as well as increased levels of chemical and physical leaching of contaminants from the waste. This has the associated benefits of improving overall leachate quality [21].

Mathematical models are powerful predictive tools to address issues related to landfill leachate management. Numerous mathematical models have been developed to simulate the generation and transport of leachate in landfills [22–24]. The current study presents a simulation of refuse age and leachate components using a mathematical formula in cells with and without leachate recirculation.

This study consists of the following parts:

(a) long-term monitoring of leachate components in two large-scale landfill cells;
(b) establishment of a mathematical model to predict leachate concentration;
(c) determination of the effect of recirculation on predicted values of the mathematical model.

2. Experimental approach

2.1. Test cells and waste analysis

Test cells used in the study were constructed at Odayeri Sanitary Landfill, one of the MSW landfills in Istanbul, Turkey. These cells are constructed according to the technical standards of a sanitary landfill. A total of 11,000 tonnes of MSW was placed into C1 and C2 at equal quantities during the period from 3 to 9 October 2001. The refuse height is 5 m and the placement area of each cell is 1250 m^2 (25 m × 50 m). Details of the cells are shown in Fig. 1.

Although not part of the core study presented and discussed in the current paper, we carried out a waste characterization study of the test cells. For this purpose, the weighly percent of each component of the MSW was determined by via samples representing the wastes placed into the cells. Characterization studies were repeated three times during the filling of the cells. The average percentages of different waste components are shown in Fig. 2. These values are average percentages of waste components obtained from characterization study carried out by 3 m^3 waste symbolizing wastes filling to cells.

Wastes were compacted by a compactor after being added to the cells. The density and porosity values of compacted wastes are shown in Table 1. The porosity value of wastes in the landfill bioreactor is recommended to be 0.5–0.6 for optimum waste degradation and moisture distribution [25]. As evident from Table 1, the porosities of wastes added to the cells are 0.618 and 0.646 for the C1 and C2 cells, respectively.

2.2. Leachate analysis

We determine the values of parameters such as biological oxygen demand (BOD), Cl^-, chemical oxygen demand (COD) and $SO_4{}^{2-}$ of leachate samples via the procedures described in the Standard Methods of APHA [26]. The above parameters were determined by the procedures described in Method Numbers of 5210-B (5-day BOD Test), 4500-B (Argentometric Method), 5220-D Closed Reflux (Colorimetric Method) and 4500-E (Turbidimetric Method), respectively.

2.3. Recirculation strategy

Leachate is recirculated to the C2 cell by horizontal drainage pipelines (Ø 150 mm) installed in the bottom of the final cover. Leachate from the C2 cell was collected in a 10 m^3 tank and transferred by centrifuge pump to another tank at a higher level and recirculated to C2 by surface infiltration methods. The details of this method are shown in Fig. 3. Total generated leachate volumes for C1 and C2 were 780 and 865 m^3, respectively, after 920 days from placement of the MSW into the cells.

The leachate recirculation operation is carried out in three stages. In the first stage, before construction of the final cover, 30 m^3 of leachate is irrigated to C2 and then the final cover is constructed. In the second stage, the recirculation operation is started 150 days after placement of the MSW. During this stage, leachate produced from C2 is completely recirculated to the cell at a rate of 1–1.5 m^3/day for 7 months. At the end of the stage, 255 m^3 of leachate had been recirculated to the cell. After 590 days from placement of the MSW, the third stage begins. During this stage, 100 m^3 of leachate is recirculated to C2. In total, 385 m^3 of the 865 m^3 of total generated leachate is recirculated to C2. Hence, 45% of the total leachate volume is recirculated by the surface infiltration method to accelerate waste stabilization. While leachates from the C1 control cell were directly discharged to the existing leachate pond within the Odayeri Sanitary Landfill, the quantity of discharged leachate was 480 m^3 ($865 - 385 = 480$ m^3).

3. Simulation method

It is well known that contaminants are released from solid wastes and transported by passing fluids. MSW contains many

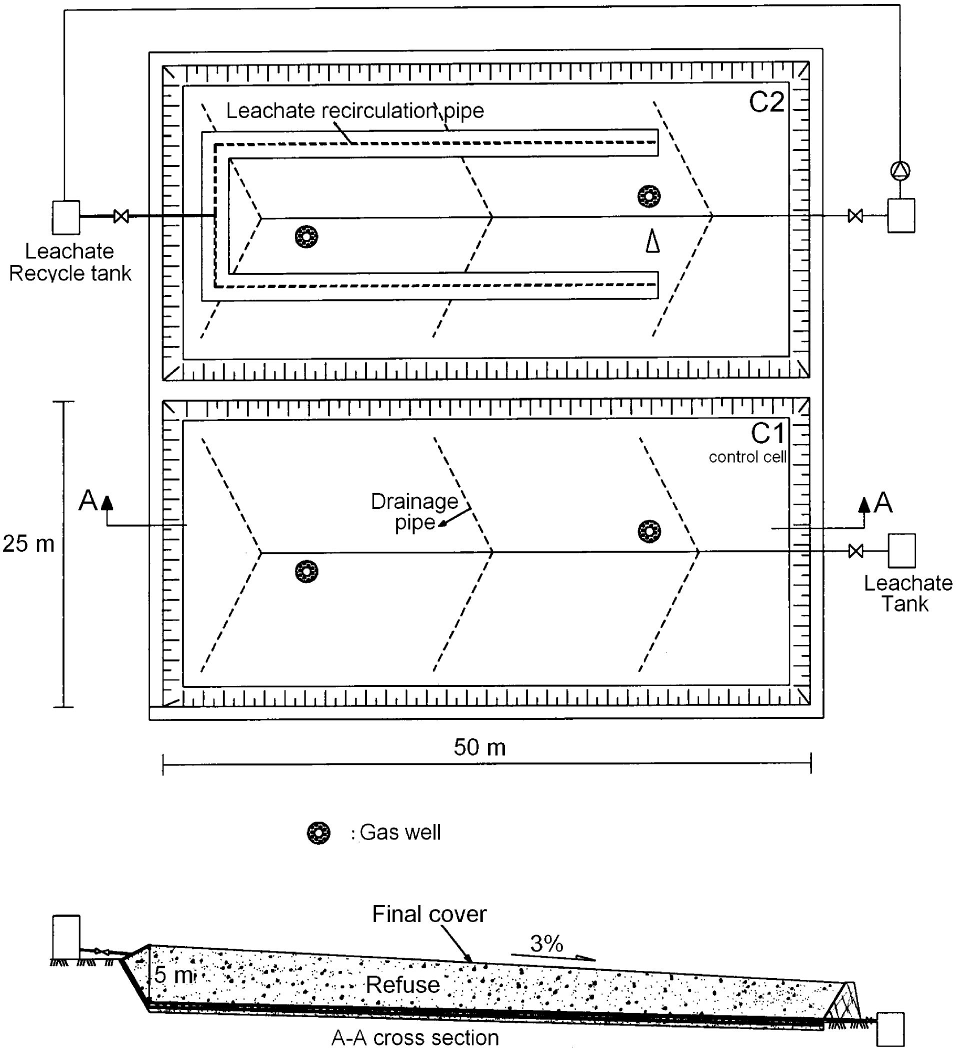

Fig. 1. Construction details of the cells.

leachate contaminants that are eventually extracted by physical washing action and microbial decomposition. The initial concentration of leachable contaminants in the solid phase depends on the characteristics of the solid waste and the extent of decomposition. As solid waste decomposes in the presence of moisture and microbial activity, the contaminants are released. The released materials are then transported by percolating liquid. Exchange of contaminants from liquid to solid can take

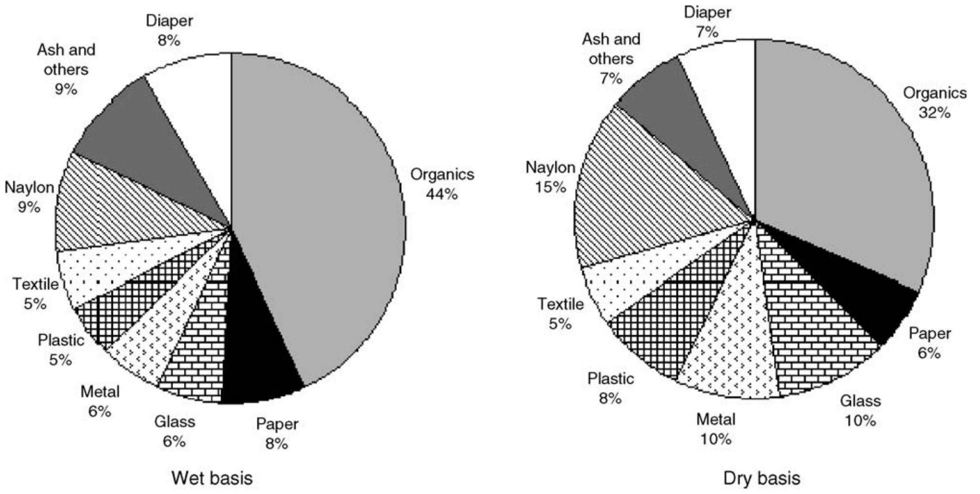

Fig. 2. Characterization of wastes placed to test cells at wet and dry basis.

Table 1
Porosity and density of wastes placed to cells

Parameter	Volume (m^3)		Mass (tonnes)		Density (tonnes/m^3)		Porosity	
	C1[a]	C2[b]	C1	C2	C1	C2	C1	C2
Test cell volume[c]	6250	6250	–	–	–	–	–	–
Waste mass	–	–	5350	5400	–	–	–	–
Waste density	–	–	–	–	0.856	0.864	–	–
Density dry basis[d]					0.529	0.525		
Porosity[e]	–	–	–	–	–	–	0.618	0.646

[a] Leachate recirculation cell.

[b] Control cell.

[c] Cell volume ($B \times L \times H = 25\,\text{m} \times 50\,\text{m} \times 5\,\text{m}$).

[d] Waste moisture content = 55%, density at dry basis = (1 − 0.55 × waste density).

[e] Porosity = 1 − [(waste volume placed to cells at dry basis)/(test cell volume)].

place via reactions such as surface-controlled adsorption and ion exchange. A contaminant species can migrate from solid to liquid by dissolution and ion exchange. The rate of decomposition and removal of contaminants from the solid phase depends upon the characteristics of the solid waste, the chemical species, initial concentration in the solid phase, volume of water percolating through the liquid and the decomposition rate of the solid waste. In this context, modeling of the leachate quality of landfills has been widely reported. Reinhart et al. [9] used the VIP model to simulate the fate of organic constituents disposed in a sanitary landfill. The model utilized data obtained from a refuse column. Gau and Chow [27] investigated the characteristics of landfills using different kinds of waste combinations. Their model considers the influences that adsorption, desorption and biological reactions in the landfilling process may have on leachate quality, and the authors establish a model of leachate quality. Yıldız et al. [20] developed a mathematical model to simulate landfill leachate behaviour and distribution of moisture and leachate constituents throughout the landfill, taking into consideration the stage of landfill development. Their model incorporates governing equations that describe processes that influence leachate production and biochemical processes taking place during waste stabilization. The model was calibrated and partially verified using data from the Keele Valley landfill in Ont., Canada.

Generally, the adopted functions are equations achieving zero pollutant concentrations, whereas pollutant concentrations remain constant from after minimum values are achieved until waste stabilization at the landfill bioreactor is complete. In particular, the organic matter concentration can remain constant as landfill becomes older. In this study, we simulate leachate contaminants from two pilot-scale landfill cells with and without leachate recirculation by a non-linear mathematical function that provides the exchange of leachate contaminants with refuse age. If this function is assumed to be an exponential function, then

$$y = a_0 + a_1 \cdot e^{-t} + a_2 \cdot t \cdot e^{-t} \tag{1}$$

where a_0, a_1 and a_2 are unknown constants of the function, the a_0 constant is residual concentration and y is pollutant concentration at time t as g/l and t is refuse age as months.

It can predict reaching rate to the peak value of pollutant concentration by via adopted non-linear exponential function. Hence, prediction model can ensure optimization of leachate treatment. Constants in the non-linear equation are solved by the least squares method, minimizing the total square deviations from the model of the experimental data, using a MATLAB 7.0® computer program.

A regression matrix for the function can be expressed as

$$\begin{bmatrix} y_1 \\ y_2 \\ y_3 \\ \vdots \\ y_n \end{bmatrix} = \begin{bmatrix} 1 & e^{(-t_1)} & t_1 \cdot e^{(-t_1)} \\ 1 & e^{(-t_2)} & t_2 \cdot e^{(-t_2)} \\ 1 & e^{(-t_3)} & t_3 \cdot e^{(-t_3)} \\ \vdots & \vdots & \vdots \\ 1 & e^{(-t_n)} & t_n \cdot e^{(-t_n)} \end{bmatrix} \times \begin{bmatrix} a_0 \\ a_1 \\ a_2 \end{bmatrix}$$

This matrix can be solved by the MATLAB® program via the following expressions:

$$X = [\text{ones}(\text{size}(t))\, \exp(-t) t \cdot \exp(-t)] \tag{2}$$

$$a = X \backslash y \tag{3}$$

in which y represents experimental data and (\) represents the inverse division operator in the MATLAB® program. The unknown constants (a_0, a_1 and a_2) of the function are obtained via this operator.

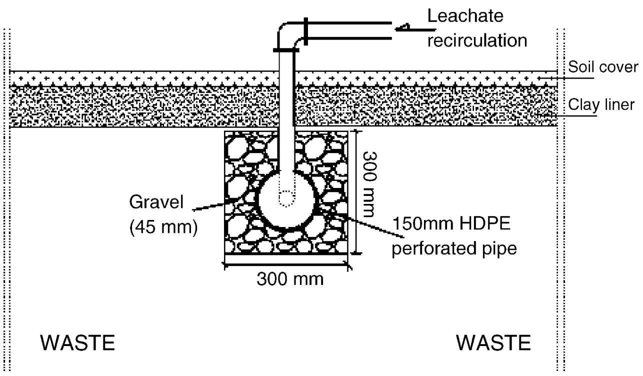

Fig. 3. Leachate recirculation system.

4. Results and discussion

4.1. COD and BOD

Young leachate from the acidic phase is characterized by high values of organic pollutants. A large portion of the organic matter consists of volatile fatty acids. As the volatile fatty acids are easily biodegradable, the ratio of BOD to COD during this phase is generally 0.4–0.5 or even higher. Leachate generated from an aged landfill has a ratio closer to zero [28]. The COD concentrations of leachate from C1 and C2 rapidly reached maximum values of 75 and 70 g/l, respectively, after nearly 1 month of landfilling. The maximum values of the COD parameter obtained by the model are 75 and 64 g/l. The maximum value of COD concentration depends upon the amount of organics and whether they are readily degraded. The COD concentration of leachate can increase rapidly when the landfill material consist of MSW. Once bioreactions occur, the organic matter tends to degrade; the COD concentration of leachate decays steadily before achieving a stable concentration. COD values reached 1500 mg/l (C1) and 700 mg/l (C2) nearly 900 days of operation. The strictest standard for sewerage systems of the ISKI (Istanbul Water and Sewerage Administration) is 800 mg/l for the COD parameter. The standard was achieved more rapidly in C2 leachate than C1 leachate thanks to the leachate recirculation operation. The BOD parameter in leachate can be evaluated as an indicator of the anaerobic decomposition rates of organics in MSW. The BOD values in C1 and C2 leachates reached maximum values nearly 1 month after the start of landfilling. This value then decreased rapidly with increasing refuse age. The maximum values of measured BOD are 52 and 63 g/l for C1 and C2 cells, respectively. BOD to COD ratios are around 0.8 for both test cells during the acidogenic phase. This ratio indicates the biological activity of the leachate. The high ratio resulted from the acid phase of the anaerobic degradation of organic matter. This ratio then decreased to 0.06.

COD and BOD loads were obtained as follows, from the relationship between monthly average COD and BOD values (C, kg/m^3) and monthly total discharged leachate quantity.

$$L\,(\text{kg/day}) = \frac{\text{Qd}\,(\text{m}^3/\text{month}) \times C\,(\text{kg/m}^3)}{30\,(\text{day/month})}$$

The change in COD and BOD loads are shown in Fig. 4. While the COD load reached minimum values (6.9 kg/day) in the C2 cell after 6 months, it reached minimum values (6.16 kg/day) in the control cell after 10 months. COD loads were 0.16 and 0.17 kg/day after 30 months in the C1 and C2 cells, respectively. Similar BOD load trends were obtained for the C1 and C2 cells, with values of 0.10 and 0.16 kg/day after 30 months, respectively. In order to gain a benefit of leachate recirculation, leachate/waste contact opportunity must be provided at a rate which does not cause leachate to accumulate excessively within the landfill. Proper management of leachate requires an understanding of a recirculating landfill water balance. Once moisture enters the landfill moisture holding capacity within the landfill may be sufficient to delay the appearance of leachate. In operations where moisture holding capacity of the waste is used approximately, in situ storage of leachate may be adequate to manage infiltrating moisture [29]. Doedens and Cord-Landwehr [30], estimated that the additional storage provided from homogenous distribution of introduced leachate amounted to some 10 times the volume of leachate generated. Considering these observations, leachate recirculation operation was carried out at C1 and C2 cells. The organic loads of the C2 test cell decreased more rapidly than the control cell due to the leachate recirculation operation.

4.2. Sulfate (SO_4^{2-})

Sulfate in wastewater can present a serious problem in the case of anaerobic treatment processes; the anaerobic treatment of sulfate-rich wastewaters deserves special attention. Several different interactions between methane-producing archaea and sulfate-reducing bacteria take place during anaerobic digestion. The results of these synthrofic or competitive interactions can compromise the successful application of anaerobic biotechnology. Sulfate emissions are not a direct threat to the environment, but high sulfate concentrations can cause an imbalance in the natural sulfur cycle. Sulfide production can present serious operational problems in anaerobic reactors that treat wastewater with high sulfate concentrations [31]. SO_4^{2-} concentration in leachate is expected to decrease with refuse age. This decrease is caused by the reduction of sulfate to sulfide coincident with the initiation of anaerobic conditions in the landfill. Hence, the

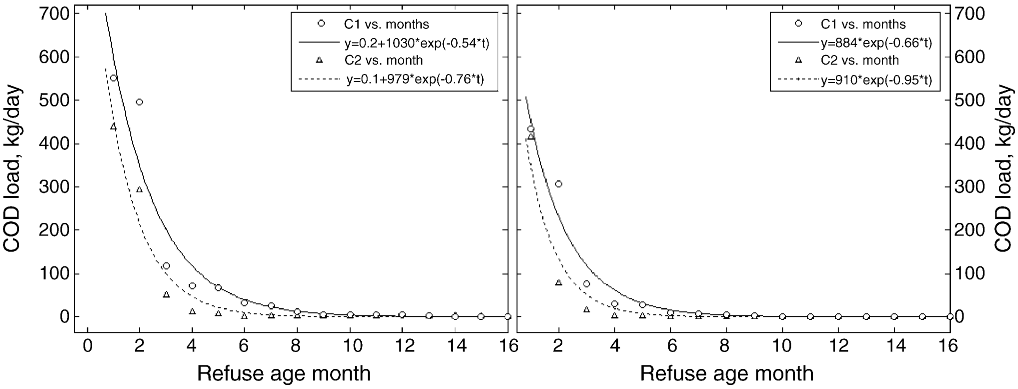

Fig. 4. COD and BOD loads of leachates from C1 and C2 test cells.

Table 2
Mathematical functions and unknown constants for simulated leachate parameter (confidence interval 0.95)

Parameter	C1			C2		
	a_0	a_1	a_2	a_0	a_1	a_2
COD	1.95	12.78	189.90	1.75	21.19	148.60
BOD	1.52	11.33	123.10	0.74	14.40	101.80
SO_4^{2-}	0	0.98	2.34	0	1.17	2.07
Cl^-	3.0	9.40	16.4	2.97	8.18	19.7

SO_4^{2-} parameter in leachate can be used as a stabilization indicator within landfills.

Sulfate concentrations in C1 and C2 leachates reached maximum values after approximately 1.5 months of landfilling before decreasing rapidly with increasing refuse age. The decrease in sulfur concentrations occurred more rapidly in C2 leachate. SO_4^{2-} concentration rapidly reached a maximum value of 2000 mg/l within 45 days, but the development of anaerobic conditions caused a sharp decrease to around 75 mg/l for C2 and 450 mg/l for C1 after 5 months of operation.

4.3. Chloride

As chloride represents a non-biodegradable conservative parameter, the change in chloride concentration is commonly used to assess variation in leachate dilution [32]. Chloride parameter in C1 and C2 leachates reached a maximum after 1 month. A sharp decrease in Cl^- concentration, from 14–15 to 5 g/l was observed after approximately 2 months of operation, followed by a slow decrease. There is no observable difference in concentrations within C1 and C2.

4.4. Model results

The unknown constants for change in simulated parameters with refuse age, and their coefficients (with 95% confidence bounds), are presented in Table 2.

Measured COD and BOD data are simulated by a mathematical function ($y = a_0 + a_1 \cdot e^{-t} + a_2 \cdot t \cdot e^{-t}$). Actual data and curves obtained from prediction data for COD and BOD parameters are shown in Figs. 5 and 6. A good fit was obtained between the measured data and the model simulations ($R^2 = 0.87$–0.92). The a_0 constant expresses the residual pollutant concentration. Measured and predicted residual COD concentrations are 1.95 and 1.5 g/l, respectively, for C1. Similarly, values of 1.75 and 0.7 g/l were determined for the C2 test cell. The SO_4^{2-} parameter is simulated for a specific refuse age according to a mathematical function. Actual data and curves obtained from predicted data for this parameter are shown in Fig. 7. The a_0 constant predicted and measured for the sulfate parameter is zero, as sulfate converts to H_2S under anaerobic conditions and is also highly

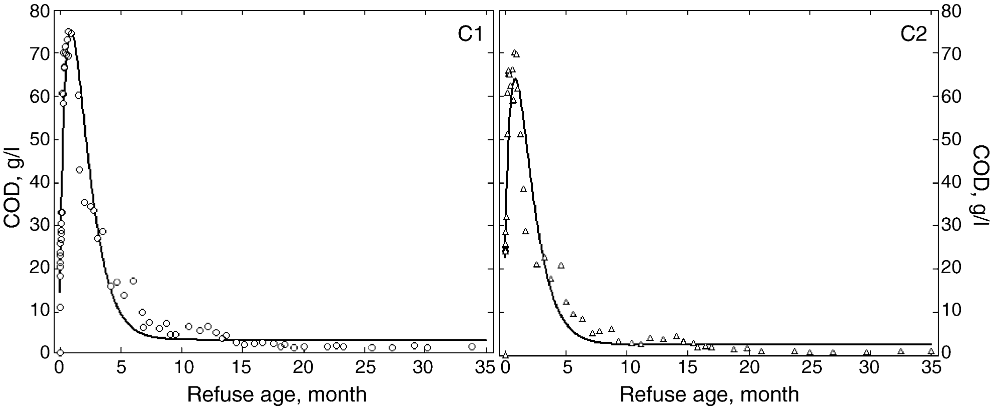

Fig. 5. Relationship between the COD parameter of C1 and C2 leachates and the refuse age.

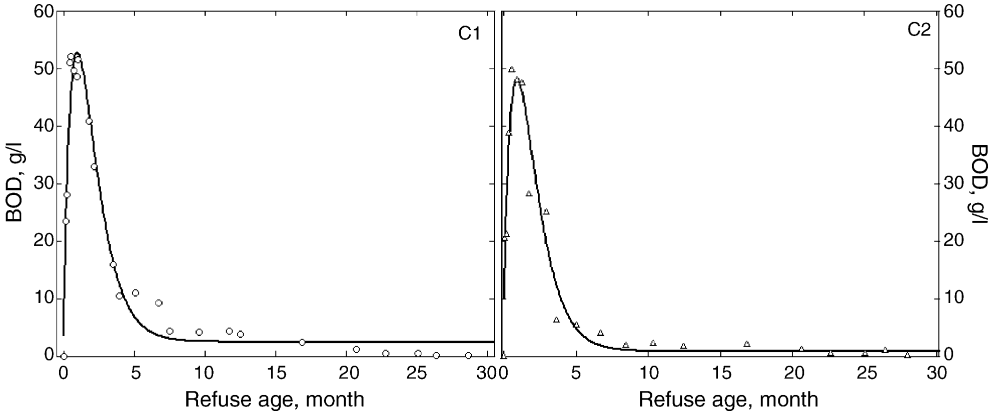

Fig. 6. Relationship between the BOD parameter of C1 and C2 leachates and the refuse age.

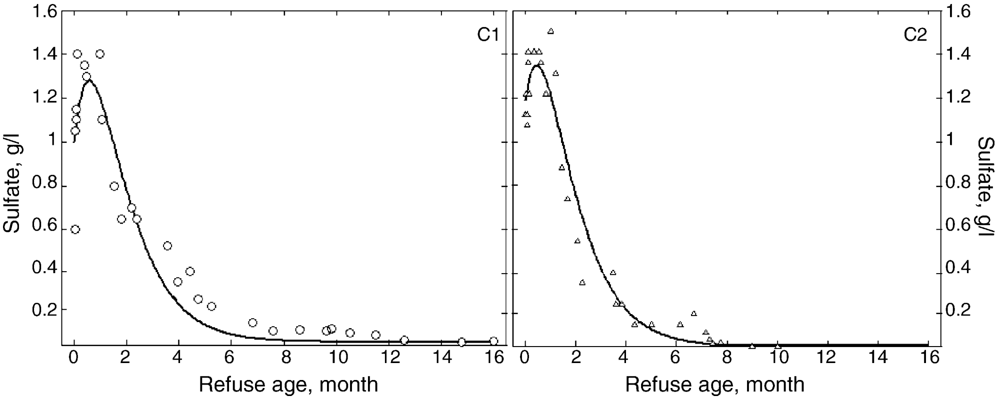

Fig. 7. Relationship between the $SO_4{}^{2-}$ parameter of C1 leachate and the refuse age.

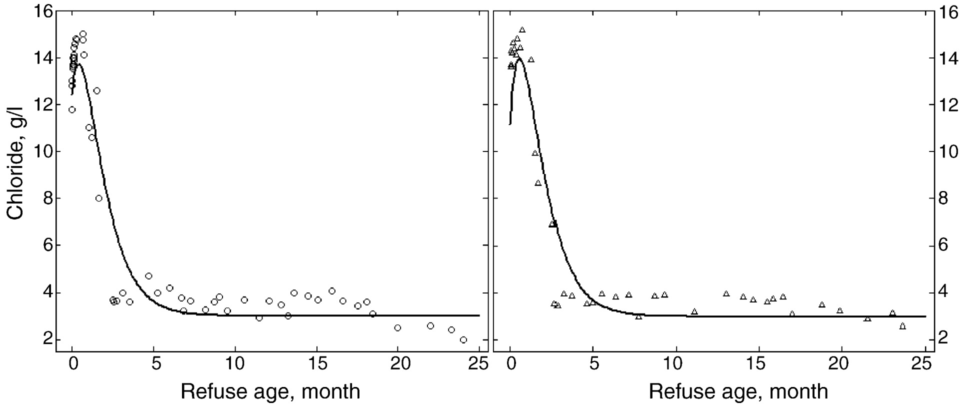

Fig. 8. Relationship between the Cl^- parameter of C1 leachates and the refuse age.

Table 3
Statistical parameters

Parameter	C1				C2			
	COD	BOD	$SO_4{}^{2-}$	Cl^-	COD	BOD	$SO_4{}^{2-}$	Cl^-
R^2	0.921	0.890	0.896	0.862	0.902	0.874	0.886	0.846
Adjusted R^2	0.919	0.883	0.891	0.860	0.900	0.862	0.880	0.841
SSE	3.249	6.734	0.261	2.008	7.634	7.519	0.265	2.255
RMSE	7.07	861.5	2.450	241.9	3031	904.6	1.889	193.2

soluble. The simulation curve and actual data for Cl^- is shown in Fig. 8.

All statistical parameters are provided in Table 3. As evident from Table 3, R^2 values are 0.85–0.92; a good fit was obtained between measured data and the model simulations. Initial examination indicates that the mathematical simulations provide better fits that explain the characteristics of the data. The fitting model for our data set was defined. With the aim of evaluating the goodness of obtained fits, we calculated the sum of squares due to error (SSE), *R*-square, and adjusted *R*-square and root mean square errors (RMSE) associated with the output model results. SSE measures the total deviation of the response values from the fit to the response values. A value closer to zero indicates a better fit. *R*-square measures how successful the fit is in explaining the variation of the data. If the number of fitted coefficients in model increases, *R*-square might increase although the fit may not improve. To avoid this situation, it should be used the degrees of freedom adjusted *R*-square statistic. This statistic uses *R*-square statistic, and adjust it based on the residual degrees of freedom. RMSE statistic is also known as the fit standard error and the standard error of the regression.

5. Conclusions

In this study, we carried out long-term monitoring of COD, BOD, sulfate and chloride concentrations from two large-scale landfills, and simulated the concentrations via mathematical formula. The reaching rate to peak values of pollutant concentration can be predicted by adopting a non-linear exponential function. The residual pollutant concentration can be predicted by the simulation model once the minimum value has been achieved, as the residual concentration is maintained until the final formation of leachate within the landfills. Hence, this predictive model can ensure optimization of leachate treatment. Leachate quality did not vary significantly between the two cells. Overall, there appeared to be little improvement in leachate quality by leachate recirculation, however, COD and BOD loads reached minimum values within the leachate recirculation cell. Accordingly, we observe that leachate treatment costs are reduced and the risk of adverse long-term environmental impacts of landfills is minimized.

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