Desalination and Water Treatment
www.deswater.com
doi: 10.1080/19443994.2014.938302

56 (2015) 622–628
October

Taylor & Francis
Taylor & Francis Group

Application of the central composite design and response surface methodology for the treatment of Kermanshah landfill leachate by a sequencing batch reactor

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Received 2 February 2014; Accepted 16 June 2014

ABSTRACT

The objective of this paper is to investigate the COD removal efficiency of the Kermanshah landfill leachate by applying the aerobic sequencing batch reactor (ASBR). The ASBR was operated to investigate the COD removal efficiency at the various hydraulic retention time (HRT) and COD concentrations. In order to study the effects of COD concentration and HRT based on response surface methodology at three-level, two-variable central composite design of experiments were used. The results showed that the leachate could be effectively treated with 90% of COD removal at the lowest COD concentration (16,000 mg/L) in influent. The removal efficiency decreased gradually down to 30.9% when COD increased to 48,000 mg/L. The system has strong tolerance to organic shock loading in this experiment. The five suggested models based on the mentioned variables were applied to predict the response values. The value of the HRT, as important variables, showed that efficiency of reactor decreased from 70 to 50%, when the HRT decreased from 6 to 2 d. This study contributed to a better understanding of the function of HRT and COD concentration in the system.

Keywords: Landfill leachate; Kermanshah; Aerobic treatment; SBR reactor; CCD

1. Introduction

Solid waste management is a complex problem that continually confronts the societies around the world, especially in developing countries, due to rapid population growth, urbanization, fast industrialization, and economic development resulting in rapid increase in solid waste production [1,2]. Generally, in developing countries because of economic limitations and simplest, the controlled and uncontrolled landfills are used as final disposal of generated solid wastes [3]. Uncontrolled dumping sites, without any concern as to their leaching and transport fate into ground waters, are the most applied method to the final dispose of waste in Iran, which have become a real risk to the environment and public health in all cities.

Landfill leachate is known as a complex wastewater due to its large variability of organic, inorganic, and heavy metal contents. The presence of moisture or water inside landfilled solid waste, higher than its field

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capacity, allows a combination of physical and microbial processes to transfer pollutants from the solid waste into the liquid resulting in the formation of leachate [4–6]. The quality and quantity of leachate is affected by many parameters such as waste type, seasonal weather variation, landfilling technique, piling and compaction method, and the landfilling age [7,8]. The age and maturity of the landfill site is based for classifying leachate into two main groups due to special chemical composition of leachate; young landfills contain very high concentrations of organic compounds (BOD and COD), whereas in old landfills the levels of organic matter are substantially lower [9,10].

Landfill leachate due to its harmful effect on the environment and human health needs to be managed by appropriate methods; among different methods, biological treatment has been used widely to treat laechate with high organic biodegradable compounds and nitrogen [9,11,12]. The most popular landfill leachate treatment is the SBR as cost-effectiveness method with several advantages such as primary clarification, secondary clarification, and treatment that can be achieved in a single reactor; minimal footprint, and operating flexibility [13].

Up to date, produced leachate from Kermanshah dumpsite without any treatment has been discharged to sterile lands and receiving waters. In order to assess and develop a low-cost treatment method, a lab-scale study was carried out and results of the work are presented in this paper. An aerobic sequencing batch reactor (ASBR) with columnar shape was operated for six months to treat the young landfill leachate with high concentrations of COD and ammonia. The objectives of this work were to investigate the effect of COD concentration and hydraulic retention time (HRT) on COD and ammonia nitrogen removal under aerobic condition with high oxygen concentration. In this regard, the central composite design (CCD) is Design-Expert software used in all the experiments. The developed polynomial models analyzed the data obtained from different runs. The sufficiency of the models was investigated via analysis of variance (ANOVA) to provide the statistical findings and diagnostic checking tests of the models.

2. Materials and methods

2.1. Experimental setup and operation conditions

A cylindrical laboratory-scale sequential batch reactor with internal diameter of 8 cm, height of 50 cm, and total working volume of 2 L was used for landfill leachate treatment. The reactor was made from glass. The reactor content was mixed with sufficient aeration (more than 4 mg O_2/L), which was provided by an air pump connected to porous stone located at the bottom of the reactor. The detailed running schedule of the SBR cycle consisted of five phases: filling time of landfill leachate, 2 min; reaction time, according to three level of HRT equal 23, 47, and 71 h; settling time, 56 min; and discharge time, 2 min. At the end of each settlement phase, 50% of the contents of the reactors were decanted from reactor and then the reactor was fed by new wastewater at different runs.

The reactor has been inoculated with mixed culture of biomass that was obtained from wastewater treatment plant of Faraman Industrial Estate, Kermanshah, Iran. After inoculation of the reactor with 4,000 mg/L mixed liquor volatile suspended solid (MLVSS), the reactor was initially fed with a leachate dilution of 10, 20, 40, 70, and 100% by volume mixed with a synthetic wastewater (consist of glucose) for adapting bacteria (activated sludge) with high COD concentration (48,000 mg/L). The mixed feed was prepared based on real concentration of COD in leachate from dumpsite. The main variables namely HRT and COD concentration were investigated, while other controlling factors such as pH, temperature, and dissolved oxygen (DO) were kept constant under wanted condition to limit their effects on the process during the experiments. The temperature was maintained at 25 ± 2˚C by contorting room temperature. The operating conditions in this research are summarized in Table 1.

2.2. Experimental design and mathematical model

The experimental design was conducted using the statistical method of factorial design of

Table 1
Operational condition of the ASBR

Parameters	*R*1
Temperature (˚C)	25 ± 2
DO (mgL^{-1})	>4
HRT (h)	48,96, and 144
Cycle (h)	24, 48, and 72
MLSS (mgL^{-1})	4,000
MLVSS (mgL^{-1})	3,250
pH	7.6 ± 0.3
COD (mgL^{-1})	16,000, 32,000, and 48,000
Volumetric exchange rate (%)	50%

experiments (Design-Expert; version 8.0.0). The method has the ability to eliminate errors systematically with an estimate of the experiment, minimize the number of experiments, and determine an empirical model based on the experiments performed [14,15]. Among such techniques, the RSM is a collection of statistical and mathematical techniques that are practical in the analysis and modeling of problems. The CCD is the standard RSM, which shown in Table 2; a CCD in the form of second-degree polynomial full factorial design was used in which two independent variables were converted to dimensionless ones ($x1$, $x2$,) with the coded values at 3 levels: −1, 0, +1. CCD also provides information on the interaction between variables based on the dependent variable [16]. The sequential model sum of squares was used to estimate the coefficients of the statistical model as suggested in the quadratic model based on Eq. (1) [14].

$$Y = \beta_{\circ} + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum_{i<j}^{k} \sum \beta_{ij} x_i x_j + \epsilon \quad (1)$$

where i represents linear coefficient, j stands for the quadratic coefficients, β is the regression coefficient, k is the number of studied and optimized factors in the experiment, and e is the random error. The presence of two factors, namely, loading and HRT ($k = 2$), allows for the derivation of Eq. (2) as follows:

$$Y = \beta_0 + \beta_1 X_1 + + \beta_2 X_2 + + \beta_{11} X_1^2 + + \beta_{22} X_2^2 + + \beta_{12} X_1 X_2 + \epsilon \quad (2)$$

As shown in Table 2, the experimental conditions for process from leachate based on CCD design with a factorial matrix of 13 steady-state runs involving two different factors. In order to perform a comprehensive analysis of the process in presence of different loadings and HRT, some dependent parameters such as COD, ammonia removal as response were evaluated. Furthermore, the ANOVA method was applied in the graphical analysis of data to accomplish the interaction between the variables and responses.

2.3. Analytical methods

Analysis was carried out on raw samples and treated landfill leachate at different stages. The pH, COD, BOD_5, MLSS, mixed liquor volatile suspended solid (MLVSS), and ammonia-nitrogen were measured according to the standard method [17]. A 5% coefficient of variation (CV) was set for all samples.

3. Result and discussion

3.1. Landfill leachate characteristics

The characteristics of the collected leachate from Kermanshah dumpsite are presented in Table 3. The

Table 2
Arrangement of the CCD for the two-level factorial of variables (HRT and COD) in the present study

	Factor A: HRT		Factor B: COD	
Run	Code	Actual value (d)	Code	Actual value (mg/L)
1	(+1)	6	(+1)	48,000
2	(0)	4	(0)	32,000
3	(0)	4	(0)	32,000
4	(−1)	2	(−1)	16,000
5	(0)	4	(0)	32,000
6	(0)	4	(0)	32,000
7	(0)	4	(0)	32,000
8	(−1)	2	(−1)	16,000
9	(+1)	6	(+1)	48,000
10	(0)	4	(0)	32,000
11	(+1)	6	(+1)	48,000
12	(−1)	2	(−1)	16,000
13	(0)	4	(0)	32,000

Table 3
Characteristics of landfill leachate

Parameters	This study	[17]	[15]	[16]
COD (mg/L)	32,000–48,000	1,533–2,580	5,400	3,500–4,200
BOD_5 (mg/L)	19,000–38,200	48–105	1,900	380–420
pH	7.5 ± 0.5	7.5–9.4	N/A	8.2–8.4
Alkalinity (CO_3Ca)	12,800–16,700	N/A	11,500–18,900	4,900–5,200
NH_3-N(mg/L)	1,320–1,751	N/A	3,500	890–994
PO_4 (mg/L)	18−48	N/A	N/A	N/A
TSS (mg/L)	1,200–2,050	SS = 159–233	N/A	N/A

Note: N/A: data unavailable.

results of the characterization studies showed that the BOD_5/COD ratio was high (about 0.5–0.8), resulting in high biodegradability of this wastewater. It can be noticed that the concentration of organic parameters and nitrogen are far beyond the Iran limits to discharge into receiving water, thus treatment of the landfill leachate is highly required. Comparing the results of characterization of the raw landfill leachate in this study with the achieved results of previous studies [18–20] illustrated that Kermanshah landfill is young (Table 3) with high concentration of organic components, which makes possible applying biological treatment methods to treat this type of wastewater.

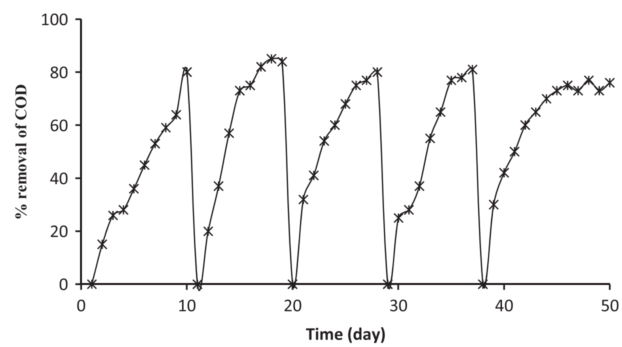

Fig. 1. Profile of COD removal during acclimatization of sludge, when HRT and final COD concentrations were 72 h and 48,000 mg/L.

3.2. Biomass acclimatization

A mixed culture containing different types of bacteria have been inoculated inside the reactor, which was provided by an activated sludge collected from an urban wastewater treatment plant located in Kermanshah, Iran. The activated sludge was adapted with low concentration of COD, and to achieve high bacteria ability the reactor have been run for 45 d with gradual increase of COD according to Fig. 1. When high COD removal achieved by the influent consists of 100% leachate, the main part of study was carried out to investigate the effect of factors namely "HRT" and "COD concentration".

3.3. Development of mathematical model and data analysis

The results of the aerobic treatment of leachate with high concentration of COD were appraised based on the CCD (Table 4). The obtained experimental data were used to develop a mathematical model (second-order polynomial equation) using ANOVA via the Design-Expert software (Table 5). The coded factors (CFs) for the percentage removal of COD as first response represent a coefficient for HRT (21.87), which is 3.37 times more than the coefficient for COD. This finding confirms that HRT contributed an effective function in the effluent concentration of COD. The CFs for the percentage removal of ammonia as second response represent a coefficient for COD (1.29), which is 2.1 times less than the coefficient for HRT. This finding indicates that COD contributed a less effective function in ammonia removal in the system. The Model *F*-value was 130.29, implying that the model is significant and there is only a 0.01% chance that this large "Model *F*-value" could occur due to noise. Values of "Prob > *F*" less than 0.05 point out that the model terms are significant and A, B, and AB are significant model terms [16,21].

As noted in Table 5, the "Lack of Fit *F*-value" was used to determine the adequacy of the model. In addition, the value of 1.1 implies that the lack of fit is not significant relative to pure error. Thus, there is

Table 4
Results of experiments according to CCD for two-level factorial of variables (HRT and COD)

Run	Factor A: HRT (d)	Factor B: COD (mgL^{-1})	COD (% removal)	NH_3-N (% removal)
1	4	32,000	57.6	10.24
2	6	32,000	80	11.75
3	4	32,000	55	11.3
4	2	16,000	44	7.57
5	2	32,000	38.77	7.13
6	6	16,000	90	16
7	4	32,000	60.8	9.7
8	4	16,000	60.85	12.96
9	6	48,000	75	8.62
10	4	48,000	50	7.97
11	4	32,000	59.2	8.99
12	2	48,000	31	5.37
13	4	32,000	57.7	1.76

a 44.50% chance that a "Lack of Fit *F*-value" this large could occur due to noise. Non-significant lack of fit is desirable, and "Prob > *F*" greater than 0.1 indicates that the model terms are not significant [14,21]. The "Pred *R*-Squared" of 0.989 is in reasonable agreement with the "Adj *R*-Squared" of 0.9818. The "Adeq Precision" measures the signal-to-noise ratio, wherein a ratio greater than 4 is desirable [14,21]. The achieved ratio of 37.95 was 9.48 times greater than the requirement of the model, which indicates an adequate signal. The developed models displayed relatively high determination coefficients (0.98, and 0.59), indicating good prediction of responses.

The response surface analysis in Figs. 2 and 3 show the effect of the operational parameters, namely, HRT and COD concentration, on the efficiency of leachate treatment during application of an ASBR. Under a COD concentration of 48,000 mg/L, COD removal significantly decreased with decreasing of HRT. The achieved results in this study as compared with previous studies on different reactors show a similar relationship between HRT and COD removal [2,11]. The effect of increasing the COD concentration on the performance of the system was studied whilst the three levels of HRT were 2, 4, and 6 d, respectively, at steady state (Fig. 2). As shown in Table 4, the percentage removal of COD was 90% with high HRT at 16,000 mg/L COD. Fig. 3 shows the effects of COD value on ammonia removal in which the inhibitory effect of organic matter on the nitrification rate is obvious. As COD increased from 16,000 to 48,000 mgL^{-1} at the HRT = 6 d, the nitrification rate decreased. However, at higher COD values (48,000 mgL^{-1}), the percentage removal of ammonia was 8.62% because of high-growth level of heterotrophic bacteria. This finding is in agreement with the results that were obtained by researchers as below:

Uygur and Kargi applied a fed-batch aerobic biological system to treat pre-treated leachate for investigating the effects of the feed wastewater COD content and flow rate on COD and ammonium ions removal. Results showed nearly 76% COD and 23% NH_4-N removals were obtained after 30 h of operation with a flow rate of 0.21 Lh^{-1}, when COD content was 7,000 mg/L [11]. In 2009, Yahmed and co-workers applied an aerobic pilot unit with three immersed and fixed biofilms reactors to treat landfill leachate. The results of experimental works indicated a high biodegradable fraction in the leachate (BOD_5/COD = 0.4), for which the biological treatment process at different organic loading rates during this study showed a significant organic matter reduction between 60 and 90% of TOC reduction [2]. Tsilogeorgis and co-workers, (2008) investigated the treatment of "mature" landfill leachate in a bench-scale membrane sequencing batch reactor (MSBR). Results indicated that the COD removal efficiency was as low as 40% and it was always below 60%. The poor MSBR performance in terms of COD removal was attributed to the high SRT, which had an apparent effect on the activity of the system's drastic biomass [9].

Table 5
Developed models and ANOVA results using Design-Expert 8.0 for studied responses

Response	Final model with significant terms coded factors (CF), and actual factors (AF)	R^2	Adj. R^2	Adeq. precision	SD	CV	PRESS	Probability for lack of fit
% COD removal	CF: + 57.61 + 21.87 × A − 6.48 × B − 0.50 × A × B + 2.89							1.1
	AF: + 32.13011 + 5.64790 × HRT (d) − 7.56789E−005 × COD (mg/L) − 1.56250E−005 × HRT (d) × COD (mg/L) + 0.72349 × HRT $(d)^2$ −4.16420E−009 × COD $(mg/L)^2$	0.9894	0.9818	37.953	2.20	3.76	158.5	
% NH_3-N removal	CF: + 8.69 + 2.72 × A − 2.43 × B − 1.29 × A × B + 0.020 × A2 + 1.05 × B2							0.083
	AF: + 7.19333 + 2.61333 × HRT (d) − 2.51146E−004 × COD (mg/L) − 4.04687E−005 × HRT (d) × COD (mg/L) + 5.00000E−003 × HRT $(d)^2$ + 4.08203E−009 × COD $(mg/L)^2$	0.5938	0.3037	5.109	2.96	32.29	110.83	

Notes: A: HRT, B: I, R^2: determination coefficient, Adj. R^2: adjusted R^2, Adeq. precision: adequate precision, SD: standard deviation. CV: coefficient of variation, and PRESS: predicted residual error sum of squares.

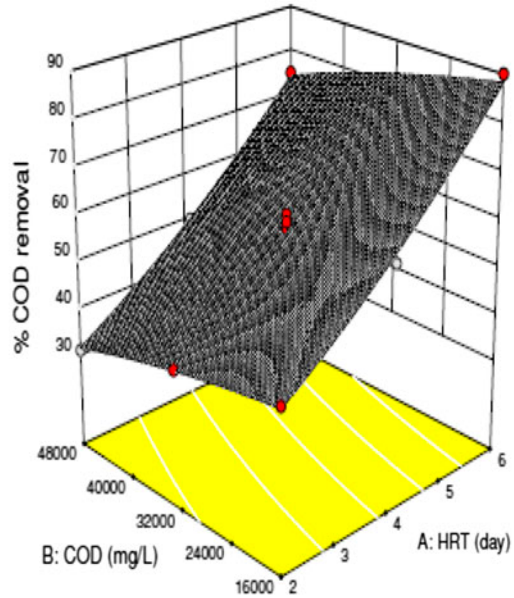

Fig. 2. The response contour plot of percentage removal of COD representing the effect of "HRT" and "COD concentration" on ASBR efficiency.

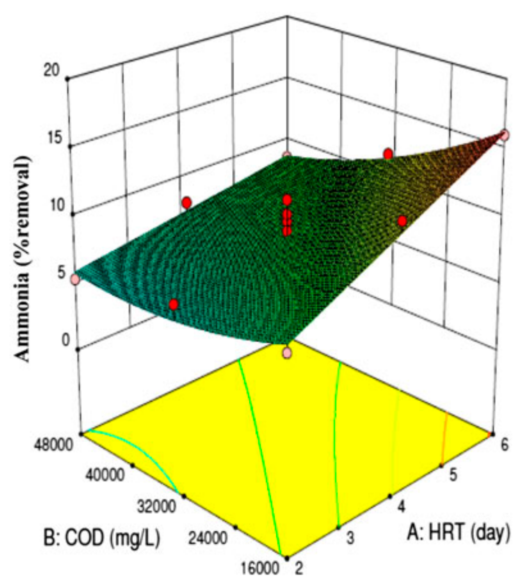

Fig. 3. The response contour plot of percentage removal of NH_3-N representing the effect of "HRT" and "COD concentration" on ASBR efficiency.

4. Conclusion

Landfill leachate treatment was accomplished using an SBR operation at different HRTs and COD concentrations, and the major conclusions attained in this research are as follows:

- The study based on leachate chemical analysis showed that the Kermanshah landfill is young and landfill leachate contains a high concentration of COD.
- The study demonstrates that the successful enrichment of mixed microbial population consists of heterotrophic and autotrophic bacteria.
- The developed models revealed significantly the effects of the HRT and COD concentration on the system efficiency, due to which the rate of COD removal decreased at the high concentrations of COD and the low HRT (2 d). The applied reactor as an aerobic and suspended system was performed for the high-rate treatment of leachate wastewater. However, high percentage removal of COD (90%) was achieved at HRT 6 d when the reactor was fed by wastewater containing 16,000 mg/L COD, but the system could not attain the discharge standard because of high concentration of COD.

Acknowledgments

Authors thank Kermanshah University of Medical Sciences for supplying the required materials and equipment in this study.

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