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ASSESSMENT OF IN-SITU AEROBIC TREATMENT OF MUNICIPAL LANDFILL LEACHATE AT LABORATORY SCALE*

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Abstract– One of the most important issues of concern in landfill management is the treatment and management of leachate. In situ aerobic treatment of landfill leachate using leachate recirculation was investigated in this research at laboratory scale. A plastic container with dimensions of 0.5 x 0.5 x 1.0 m was used as a reactor. Two sets of aeration pipes were placed inside the reactor and connected to an air compressor in order to inject air into the waste mass. Leachate was collected in a container at the bottom and pumped to another container at the top, from which leachate was recirculated back into the waste mass. The output of the screen unit of Isfahan composting plant was used as waste material. The composition of the waste was modified by adding crushed glass and shredded paper, plastic and metal containers to obtain the same composition of the collected waste. Twenty eight liters of leachate was recirculated daily for 75 days. Samples of the leachate were collected and analyzed for COD, TDS, TSS, pH, heavy metals and temperature. Total COD removal efficiency of the system was 91%. Temperature increased initially and reached a maximum of 53 °C due to rapid biodegradation of the organic matter. As the biodegradation slowed down, less heat was generated and as a result the temperature inside the reactor dropped. Both TDS and TSS showed an initial rise due to recirculation of leachate. Then, biodegradation of organic matter over time resulted in a decrease in both TDS and TSS. The removal efficiencies of the system for TDS and TSS were 56% and 34%, respectively. Removal efficiencies of 93%, 90%, 43% and 76% for Mn, Fe, Pb and Zn were respectively observed.

Keywords– Leachate treatment, leachate recirculation, aerobic treatment, in-situ, bioreactor

1. INTRODUCTION

Continuing growth of population and industrialization around the world has resulted in increasing production of municipal solid wastes (MSW), which has become a worldwide issue. Landfilling continues to be the major method of MSW management. Despite increases in recycling, composting, and incineration, approximately 54% by weight of the MSW generated in the United States in 2007 was deposited in sanitary landfills [1].

One of the most important issues of concern in landfill management is the production of landfill leachate and its potential for degrading water resources systems. Landfill leachate is defined as aqueous effluent generated as a consequence of rainwater percolation, solid wastes moisture, water production due to biochemical processes, and ground water entering waste mass during and/or after operation and closure of a landfill. According to some researchers, the negative environmental impacts of leachate leakage and migration could last for several decades [2, 3].

Leachate composition varies significantly among landfills, depending on waste composition, waste age, climate, hydrogeological conditions and landfilling technology. However, the main characteristic of

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landfill leachate is high concentrations of organic matter and as a result, high concentrations of BOD and COD. Characteristics of leachate from some of the landfills in Ontario, Canada are presented in Table 1 [4]. Comparing the concentrations of the BOD of leachate with the BOD of municipal wastewater (200 – 300 mg/L) shows the high concentrations of organic matter in leachate, and as a consequence its high pollution potential.

To prevent the adverse impacts of landfill leachate on aquatic life and the degradation of water resources, landfill leachate has to be collected and treated before its final discharge into the environment. Landfill leachate treatment methods can be classified into three major groups: (a) leachate transfer: recycling and combined treatment with domestic sewage, (b) biodegradation: aerobic and anaerobic processes, and (c) chemical and physical methods [5]. Rotating biological contactors, trickling filters, aerated lagoons, up flow anaerobic sludge blanket reactor, chemical oxidation, adsorption, chemical precipitation, coagulation/flocculation, sedimentation, flotation, reverse osmosis, and air stripping are some of the ex-situ leachate treatment methods reported in the literature [6-14].

Table 1. Characteristics of leachate produced at different landfills in Ontario*

	Ontario Landfills	CWM**	Trail Rd	Glenridge	Guelph	Burlington
pH		5.8	6.7	7.3	7.4	7.1
Conductivity (mmhos/cm)	6088		9833	6175	8621	6521
TDS	4327				4500	6214
Alkalinity	2626		5459	2555	3633	2390
BOD_5	4976		14176	28	18153	1971
COD	7855	35000	16050		21514	4525
TN	256		2488	237	606	167
Ammonia	171		318.8	206	300	152
Boron	10.5	3.23	2.52	3.1	43.3	3.02
Calcium		2140		188	203	290
Copper	0.11	0.03	0.11	0.002		0.09
Iron	131	11.5	395	39.5	28.3	79.8
Magnesium	232	374	439	281	311.6	219
Manganese	2.7	14		0.29	0.31	4.9
Nickel	0.07	0.53		0.08	0.09	0.09
Sulphate		480	49	67	0.9	92
Lead	0.05	0.1	0.04	0.03	0	0.12
Zinc	1.47	4.13		0.07	0.09	3.9

* All parameters in mg/L unless indicated otherwise
** Canadian Waste Management, Ottawa

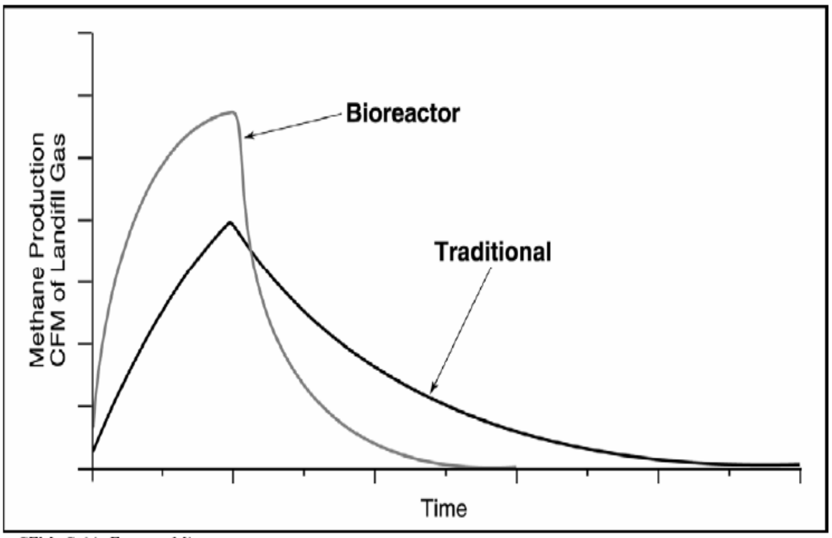
Conventional treatment systems are costly and require a long-term commitment. Moreover, great variations in strength and flows of leachate as well as its toxic effect, due to the presence of high concentrations of heavy metals and/or organic substances, make the use of these systems undesirable [15,16]. As an alternative, landfill leachate may be recirculated within the waste pile to enhance the stabilization of the organic contents [17]. Leachate recirculation is also reported to reduce leachate organic strength and toxicity of leachate, accelerate landfill stabilization, reduce landfill active life and increase landfill gas production [18-20].

As mentioned above leachate composition varies significantly among landfills. Waste composition, and as a consequence leachate composition in developing countries such as Iran is significantly different from the leachate produced in developed countries. One of the significant differences in terms of waste composition is the fraction of organic waste (food waste), which could greatly affect some characteristics of the leachate such as BOD and COD. In addition, other factors such as climate, hydrogeological conditions and landfilling technology could affect the performance and treatability of leachate.

Considering the information presented above, the aim of this research was to investigate in-situ aerobic treatment of municipal landfill leachate by leachate recirculation.

2. LITERATURE REVIEW

Conventional landfills in the United States that are designed and operated in accordance with the principles described in Subtitle D of the Resource Conservation and Recovery Act generally employ systems that minimize the amount of moisture entering and retained in the waste. The intent is to minimize the risk of groundwater pollution by limiting the amount of leachate and gas that is generated. High expenses of leachate treatment along with a better understanding of landfill decomposition processes have resulted in a shift in the philosophy of landfill design from the storage concept towards a process-based (or bioreactor) approach in recent years. The concept of bioreactor was first introduced by Pohland in the late 70's [21]. Solid Waste Association of North America (SWANA) defines bioreactor landfill as "any permitted Subtitle D landfill or landfill cell where liquid or air is injected in a controlled fashion into the waste mass in order to accelerate or enhance biostabilization of waste". Bioreactor landfills are classified as aerobic, anaerobic, and aerobic-anaerobic. In an aerobic bioreactor landfill, leachate is removed and re-circulated, often with additional water, into the landfill in a controlled manner. Air is simultaneously injected into the waste mass, using vertical or horizontal wells, to promote aerobic bacterial activity and to accelerate waste degradation. Figure 1 depicts typical gas production curves from a dry tomb landfill and a bioreactor simulating the first order biological decomposition rate (K) expected under bioreactor operation vs. the Subtitle D landfill with no liquids added using US EPA's Landgem model.



CFM=Cubic Feet per Minute

Fig. 1. Typical landfill gas prediction curve for bioreactor landfill vs. traditional landfill [21]

Bioreactor landfills require certain specific management activities and operational modifications to enhance microbial decomposition processes. Aeration, size reduction, addition of nutrients, compaction, pH adjustment and leachate recirculation has been reported to enhance the performance of bioreactor landfills [22]. The most important and cost-effective method for enhancing biodegradation in a bioreactor landfill is liquid addition, i.e. leachate recirculation. Leachate recirculation increases the moisture content in a controlled reactor system and provides the distribution of nutrients and enzymes between methanogens and solid/liquids [19].

Benefits of operating a landfill as a bioreactor include enhancement of the landfill gas (LFG) generation rates; reduction of environmental impacts, production of the end product that does not need landfilling, overall reduction of landfilling cost, rapid settlement and increased landfill capacity; improved leachate quality; reduction of post-closure activities; and the abatement of greenhouse gases [23]. However, if too much leachate is recirculated, problems such as saturation, ponding, and acidic conditions may occur. Limited data are available on the application of different leachate recirculation regimes to the waste matrix. For anaerobic bioreactors, it is recommended that leachate should be introduced slowly, since high flow rates may deplete buffering capacity and remove methanogens. As gas production is established, the flow rates and the frequency of recirculation could be increased [24].

Read *et al.* reported on the successful operation of two separate aerobic landfill systems in Georgia, USA [25]. The key to the aerobic landfill's effectiveness was the proper control of aerobic conditions, whereby waste mass temperatures and moisture were maintained within optimal ranges. Waste mass temperatures and moisture remained stable between 40 and 60°C and above 50% (w/w), respectively, in the most active areas after aerobic conditions had been reached. Methane concentrations decreased by at least 80% in the three weeks after system startup and remained consistently below15 % (v/v) for most of the project. BOD of the leachate was reduced by at least 70%. Landfills' leachate treatment needs were also reduced by 85%.

Cossu *et al.* compared aerobic and anaerobic experimental bioreactor columns. Aeration of the waste mass, either with forced aeration or in semi-aerobic like conditions, produced a rapid and marked oxidation of organics and nitrogen [2].

Application of in-situ aeration of old landfills was investigated by Ritzkowski et al. [26]. It was concluded that in-situ landfill aeration was a promising method for reducing the remaining potential emission of the landfilled waste once landfill gas extraction and utilization had come to an end.

A particular type of the in-situ aeration technology, known as the Fukuoka method, was developed in Japan and was first tested in the construction of the Shin-Kamata Landfill in 1975. This semi-aerobic landfilling method is a standard type of landfill currently used in Japan. In the Fukuoka method, air is allowed to passively move through the headspace of the leachate collection system pipes that are open to the atmosphere. The temperature difference between the interior landfill and the outside air produces a chimney effect, where air is drawn into the pipes and circulated throughout the waste mass. This technology has been used in Malaysia, China, and Iran (Kahrizak Landfill) [27, 28].

It has been reported that in addition to the reduction and removal of organic matter, leachate recirculation is an effective way to reduce the metals content of leachate [29]. Erses *et al.* investigated the sorption capacity of solid waste for selected heavy metals (Cd, Ni, Cu, Zn and Fe) in landfills [30]. The sorption capacity of the domestic solid waste matrix for heavy metals was quite significant with an experimental maximum metal sorption of 205 mg/kg for Fe, 125 mg/kg for Zn, 100 mg/kg for Cu, 38 mg/kg for Ni, and 18 mg/kg for Cd from individual solutions. Bilgili *et al.* investigated the metal concentrations of simulated aerobic and anaerobic pilot scale landfill reactors. They stated that metals concentration in the leachate decreased as a result of metal precipitation in the landfill body [31].

3. MATERIALS AND METHODS

Figure 2 shows the laboratory set up used for the experiments. The reactor was a plastic container with a cross section area of 0.5 x 0.5 m, and a height of 1 m. Two sets of aeration pipes were placed in the middle and the bottom of the reactor and connected to an air compressor in order to inject air into the waste mass at a rate of 0.24 lit/min.kg of waste. Leachate was collected in a container at the bottom and pumped to another container at the top, from which leachate was recirculated back into the waste mass. The output of the screen unit of the Isfahan composting plant was used as waste material. The composition of the waste was modified by adding crushed glass and shredded paper, plastic and metal containers to obtain the same composition of the collected waste. Although due to limited resources and the size of the reactor only one reactor was constructed and maintained for 75 days, taking into account the considerable size of the reactor, it is expected that for the same environmental conditions and composition of waste material the results should be relatively comparable and repeatable. Other researchers such as San and Onay and Oliver and Gourc encountered the same limitations and had used a single reactor of an almost similar size for conducting their experiments [24, 32]. Nevertheless, the obtained results are based on this set of experiments conducted by one reactor.

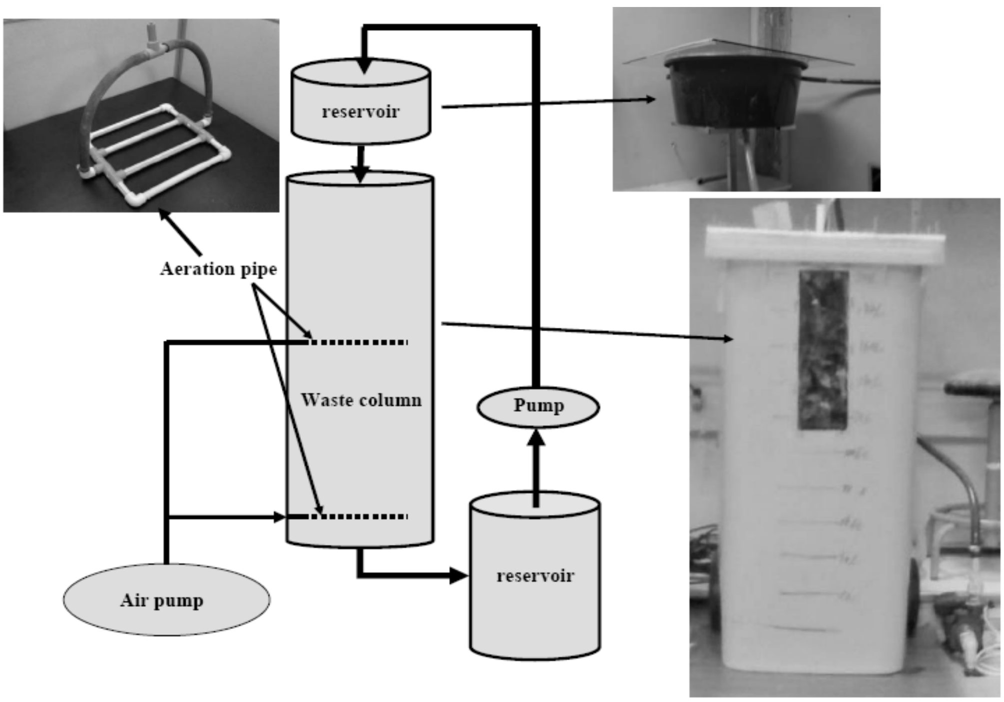


Fig. 2. The experimental aerobic bioreactor setup

Table 2 represents the composition of the modified waste used in the experiment. As presented, the organic content of the waste, like most developing countries, is very high. The maximum size of waste particles was 8 cm. The waste was placed into the reactor in layers and compacted to achieve a density of 550 Kg/m^3. A stone layer was placed at the bottom as a drainage layer. Another stone layer was placed at the top in order to enhance uniform distribution of the leachate from the top. Finally, the bioreactor cell cover was replaced on top of the reactor.

Table 2. Composition of the waste used in the experiment (in percent)

Organic matter	Plastic	Paper & cardboard	Textile	Glass	Metal
78	10	5	3	2	2

Fresh leachate from leachate containers installed in waste collection vehicles was collected and transferred to the laboratory. The moisture content of the solid waste was brought to field capacity by adding leachate to the bioreactor cell, until the amount of leachate collected from the cell equaled the amount of leachate added. Twenty eight liters of leachate was recirculated daily for 75 days. Samples of the leachate were collected and analyzed for COD, TDS, TSS, pH and heavy metals concentrations. Three replicates were used for each sample. The internal temperature of the reactor was monitored on a regular basis.

4. RESULTS AND DISCUSSIONS

The variation of the average COD of the leachate is presented in Fig. 3. Since the putrescible fraction of MSW generated in developing countries is high (40-85%), the organic matter concentration of the produced leachate is high. The initial COD of the leachate was 40500 mg/L, which reached a maximum value of 44800 mg/L after 3 days. This increase was due to rapid initial dissolution and release of the organic matter contained in WSM. After acclimatization and establishment of microorganisms, rapid biodegradation of organic matter started. As can be seen, the major reduction of COD has occurred during the period of day 3 to day 27, where COD of the leachate was reduced from 44800 mg/L to 8450 mg/L. This is equal to 81% reduction. From day 27 until day 75, COD of the leachate was further reduced to 3840 mg/L showing a total COD removal efficiency of 91%. This shows that landfill leachate management using aeration plus leachate recirculation is a promising and feasible way for in-situ treatment of the landfill leachate.

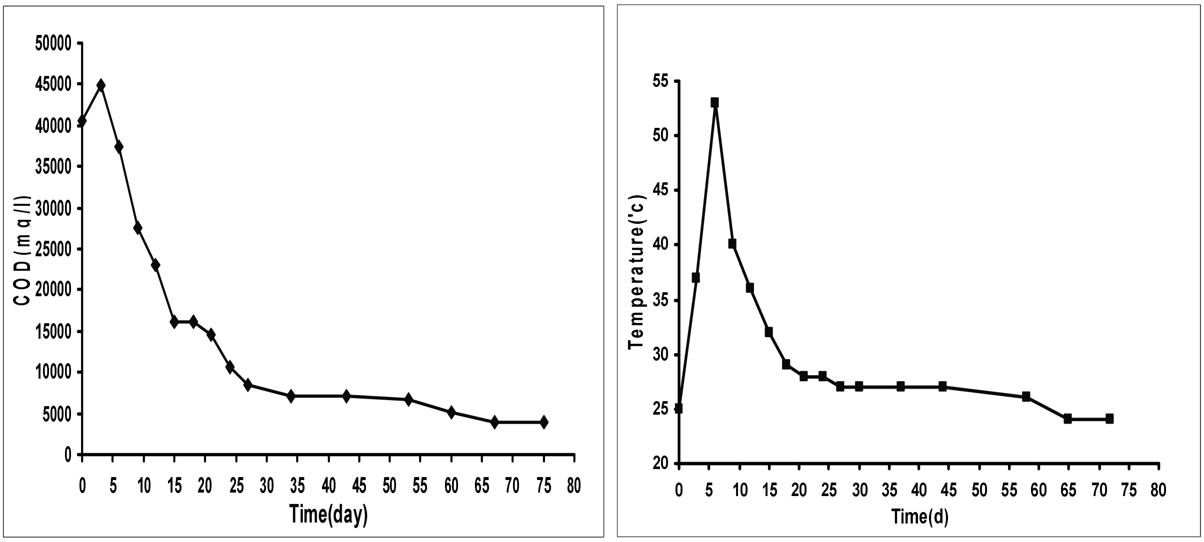


Fig. 3. Variation of COD (left) and temperature (right) of leachate against time

The average temperature variation of the reactor is presented in Fig. 3. As shown, the temperature increased initially and reached a maximum of 53 °C and then dropped back to values in the range of 25 to 30 °C. High temperatures during the rapid biodegradation of the waste could also result in inactivation of pathogens and parasites. The trend of temperature variation was similar to that of COD. This was due to the fact that heat generation was the result of microbial activity and organic matter degradation, and followed the trend observed for COD.

The variation of average pH during the experiment is shown in Fig. 4. The initial pH was 3.9, which increased to 8.2 after 27 days and remained in the range of 8.2 to 8.5 for the rest of the experiment.

Figure 5 shows the variation of the average TDS (total dissolved solids) of the leachate. Initial rise and subsequent decrease in TDS followed the same trend as the COD and temperature variations. The initial rise was due to the recirculation of leachate. TDS was increased from the initial value of 22280 mg/L to the maximum value of 28360 mg/L and then dropped to 12370 mg/L at the end of the experiment, showing a total 56% reduction for dissolved solids.

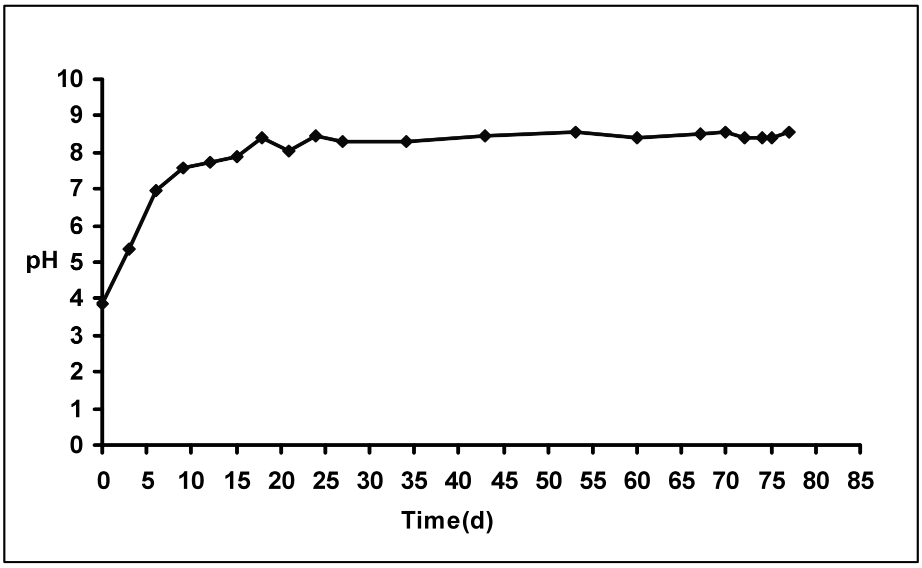


Fig. 4. pH variation of leachate against time

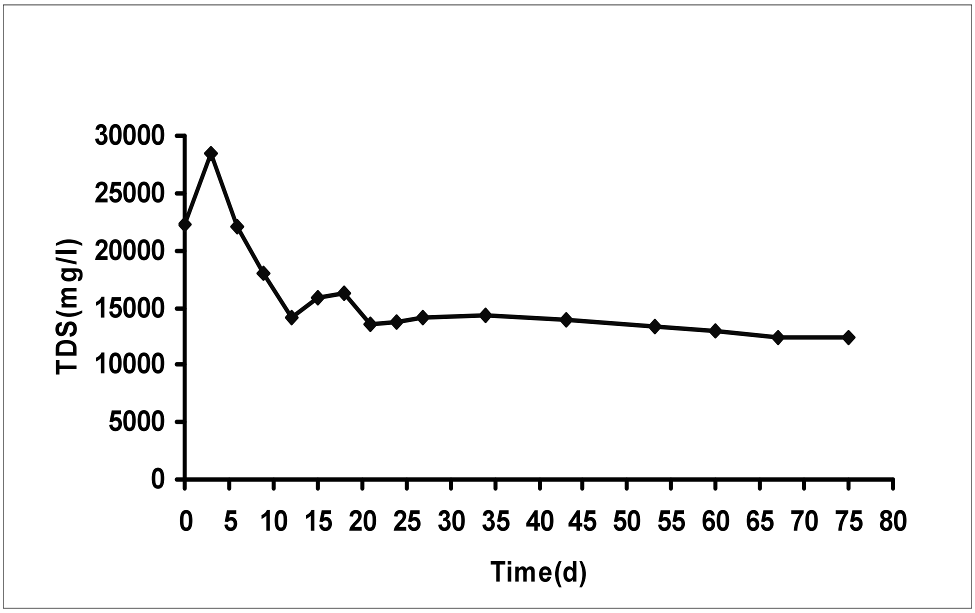


Fig. 5. TDS variation of leachate against time

The variation of average TSS (total suspended solids) of leachate is presented in Fig. 6. As in the case of TDS, leachate dissolved and collected more material due to recirculation, and hence there was an initial rise. The initial TSS of the leachate at the beginning of the experiment was 1460 mg/L, which reached a maximum level of 6700 mg/L after 24 days and then dropped to 965 mg/L at the end of the experiment. The total efficiency of the reactor for TSS reduction was about 34%.

Maximum TDS occurred sooner than maximum TSS since TDS represents the dissolved solids, which dissolve easily in the early stages of leachate recirculation. On the other hand, TSS represents suspended solids and as larger waste particles decompose and disintegrate over longer periods of time it would take more time to see the peak value compared to the dissolved species.

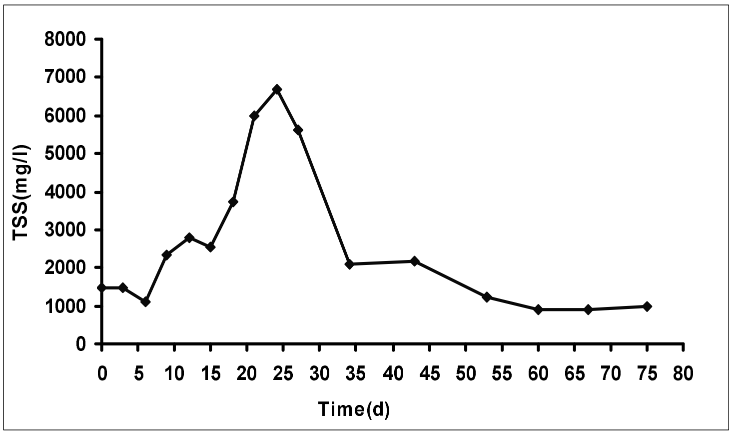


Fig. 6. TSS variation of leachate against time

Figure 7 presents the average concentrations of heavy metals (Fe, Mn, Pb and Zn) in the leachate. Leachate recirculation through MSW was very effective in reducing the heavy metal content of the leachate. The main mechanisms for the removal of heavy metals were most probably the adsorption of the heavy metals in the leachate when it was recirculated through the waste, and precipitation due to pH increase over time. Removal efficiencies for Mn, Fe, Pb and Zn were 93%, 90%, 43% and 76%, respectively. The obtained results are in agreement with the results reported in the literature. As mentioned above, solid waste material had a significant adsorption capacity for heavy metals [30]. It has also been reported that the decrease in metals concentration in leachate in a pilot scale landfill reactor was due to metal precipitation in the landfill body [31].

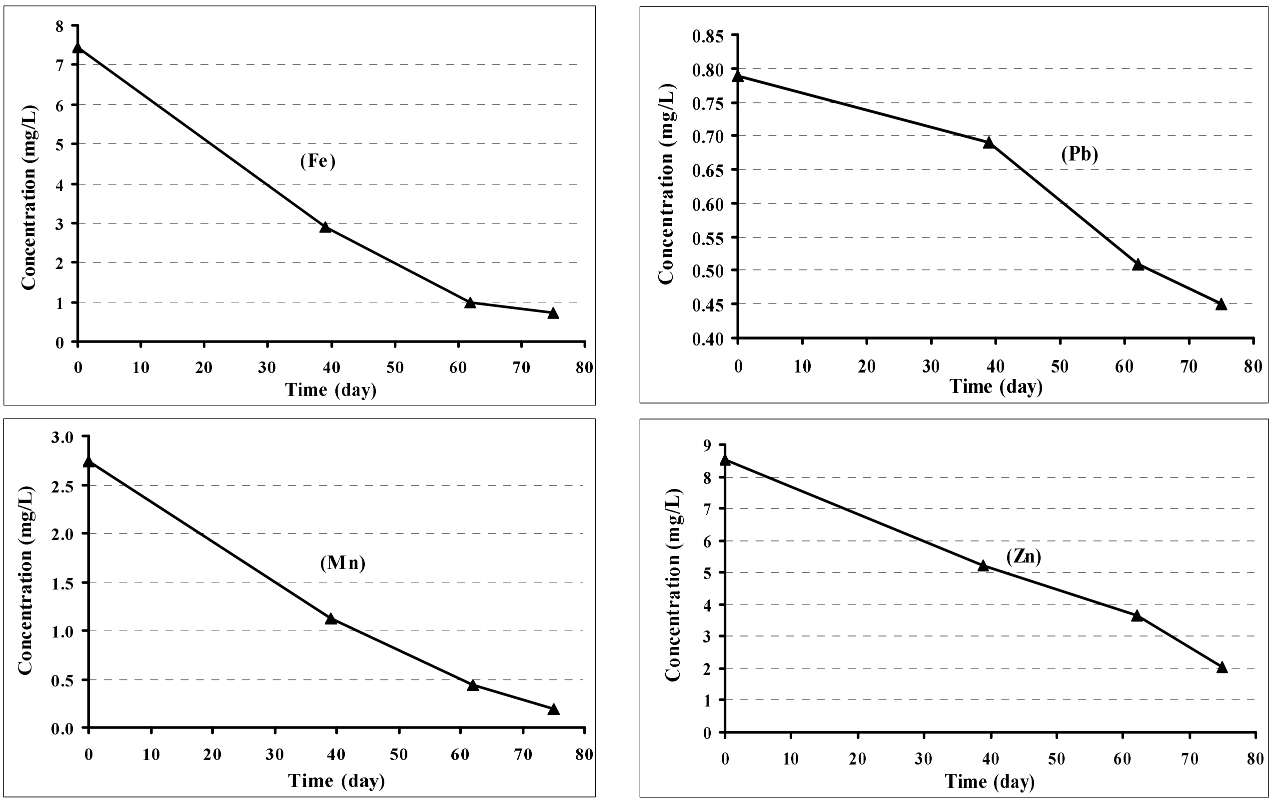


Fig. 7. Concentrations of heavy metals against time

5. CONCLUSION

The results proved that an aerobic bioreactor system using aeration and leachate recirculation was very effective for the treatment of municipal landfill leachate. This system was quite effective in terms of the reduction and biodegradation of the organic matter content of the leachate measured by COD. COD reduction occurred during two phases, a rapid reduction phase followed by a slow biodegradation phase with a total removal efficiency of 91%. Since heat is generated during biodegradation of organic matter, the pattern of temperature variation was the same as that of COD. Temperature increased initially and reached a maximum of 53 °C due to the rapid biodegradation of the organic matter. As the biodegradation slowed down, less heat was generated and as a result the temperature inside the reactor dropped. High temperatures inside the landfill could result in inactivation of pathogens and parasites, which is another advantage of this treatment technology. Both TDS and TSS showed an initial rise due to the recirculation of leachate, so, the biodegradation of organic matter over time resulted in a decrease in both TDS and TSS. The removal efficiency of the system for TDS and TSS were 56% and 34%, respectively. The aerobic bioreactor system was also effective in reducing the concentration of heavy metals through the adsorption of metals on waste material and precipitation due to the increase in pH. Removal efficiencies of 93%, 90%, 43% and 76% for Mn, Fe, Pb and Zn were respectively observed.

REFERENCES

1. US EPA., (2008). *Municipal solid waste in the United States: 2007 Facts and Figures*. United States Environmental Protection Agency, Office of Solid Waste (5306p), EPA530-R-08-010, November 2008.
2. Cossu, R., Raga, R. & Rossetti, D. (2003). The PAF model: an integrated approach for landfill sustainability. *Waste Manage*, Vol. 23, pp. 37–44.
3. Kruempelbeck, I. & Ehrig, J. G. (1999). Long-term behavior of municipal solid waste landfills in Germany. *Proceedings of the Seventh International Waste Management and Landfill Symposium*, Cagliari, Italy, October 4–8.
4. Sartaj, M. (2001). Treatment and transport modeling of landfill leachate contaminants in an engineered wetland system. Ph.D. Thesis, University of Ottawa, Ottawa, Ontario, Canada.
5. Renou, S., Givaudan, J. G., Poulain, S., Dirassouyan, F. & Moulin, P. (2007). Review, Landfill leachate treatment: Review and opportunity. *Journal of Hazardous Materials*.
6. Cossu, R., Serra, R. & Muntoni, A. (1992). Physico-chemical treatment of leachate. *Landfilling of waste leachate*, Edited by Chistensen, T. H., Cossu, R. & Stegmann, R., Elsevier Ltd., pp. 265–304.
7. Chianese, A., Ranauro, R. & Verdone, N. (1999). Treatment of landfill leachate by reverse osmosis. *Water Research*, Vol. 33, No. 3, pp. 647–652.
8. Li, X. Z., Zhao, Q. L. & Hao, X. D. (1999). Ammonium removal from landfill leachate by chemical precipitation. *Waste Manage*, Vol. 19, pp. 409–415.
9. Lin, S. H. & Chang, C. C. (2000). Treatment of landfill leachate by combined electro-Fenton oxidation and sequencing batch reactor method. *Water Research*, Vol. 34, No. 17, pp. 4243–9.
10. Henderson, J. P., Besler, D. A., Atwater, J. A. & Mavinic, D. S. (1997). Treatment of methanogenic landfill leachate to remove ammonia using a rotating biological contactor (RBC) and a sequencing batch reactor (SBR). *Environ. Technol*, Vol. 18, No. 7, pp. 687-698.
11. Trebouet, D., Schlumpf, J. P., Jaouen, P. & Quemeneur, F. (2001). Stabilized landfill leachate treatment by combined physico-chemical-nanofiltration processes. *Water Research,* Vol. 35, No. 12, pp. 2935–42.
12. Berrueta, J. & Castrillo, N. L. (1992). Anaerobic treatment of leachates in UASB reactors. *Journal Chem Technol Biotechnol*, Vol. 54, pp. 33–7.

13. Kennedy, K. J. & Lentz, E. M. (2000). Treatment of landfill leachate using sequencing batch and continuous flow upflow anaerobic sludge blanket (UASB) reactors. *Water Research, Vol.* 34, No. 14, pp. 3640–56.
14. Hoilijoki, T. H., Kettunen, R. H. & Rintala, J. A. (2000). Nitrification of anaerobically pretreated municipal landfill leachate at low temperature. *Water Research*, Vol. 34, No. 5, pp. 1435–46.
15. Vesilind, P. A., Worrell, W. A. & Reinhart, D. R. (2002). Solid Waste Engineering. Brooks/Cole Thomson Learning, U.S.A.
16. McLellan, J. K. & Rock, C. A. (1988). Pretreating landfill leachate with peat to remove metals. *Water, Air, and Soil Pollution*, Vol. 37, pp. 203-215.
17. Townsend, T. G., Miller, W. L., Lee, H. & Earle, J. F. K. (1996). Acceleration of landfill stabilization using leachate recycle. *ASCE Journal of Environmental Engineering,* Vol. 122, No. 4, pp. 263-268.
18. He, R., Liu, X., Zhang, Z., Shen, D. (2007). Characteristics of the bioreactor landfill system using an anaerobic–aerobic process for nitrogen removal. *Bioresource Technology*, Vol. 98, pp. 2526–2532.
19. Sponza, D. T. & Agdag, O. N. (2004). Impact of leachate recirculation and recirculation volume on stabilization of municipal solid wastes in simulated anaerobic bioreactors. *Process Biochemistry,* Vol. 39, pp. 2157–2165.
20. Cameron, R. D. & Koch, F. A. (1980). Toxicity of Landfill Leachate. *J. of WPCF*, Vol. 52, No. 4, pp. 760-769.
21. IT & RC, (2006). *Characterization, design, construction, and monitoring of bioreactor landfills. Technical/Regulatory Guideline, ALT-3*. Washington, D.C.: Interstate Technology & Regulatory Council, Alternative Landfill Technologies Team.
22. Reinhart, D. R., McCreanor, P. T. & Townsend, T. (2002). The bioreactor: Its status and future. *Waste Management and Research*, Vol. 20, pp. 172–186.
23. Warith, M. (2002). Bioreactor landfills: experimental and field results. *Waste Management,* Vol. 22, pp. 7–17.
24. San, I. & Onay, T. T. (2001). Impact of various leachate recirculation regimes on municipal solid waste degradation, *Journal of Hazardous Materials*, Vol. 87, pp. 259–271.
25. Read, A. D., Hudgins, M., Harper, S., Phillips, P. & Morris, J. (2001). The successful demonstration of aerobic landfilling - The potential for a more sustainable solid waste management approach? *Resources, Conservation and Recycling*, Vol. 32, pp. 115–146.
26. Ritzkowski, M., Heyer, K. U. & Stegmann, R. (2006). Fundamental processes and implications during in situ aeration of old landfills. *Waste Manage*, Vol. 26, pp. 356–372.
27. Chong, T. L., Matsufuji, Y. & Hassan, M. N. (2005). Implementation of the semi- aerobic landfill system (Fukuoka method) in developing countries: a Malaysia cost analysis. *Waste Manage*, Vol. 25, pp. 702–711.
28. Fakharian, K., Alami, R. & Abdi, M. (2003). Investigating the stability of Fukuoka method landfill at Kahrizak landfill, Tehran, (in Persian). *6th International Conference on Civil Engineering (ICCE2003),* Isfahan, Iran.
29. Christensen, T. H., Kjeldsen, P., Bjerg, P. L., Jensen, D. L., Christensen, J. B., Baun, A., Albrechtsen, H. J. & Heron, G. (2001). Review: biogeochemistry of landfill leachate plumes, *Appl. Geochem*, Vol. 16, pp. 659–718.
30. Erses, S. A., Fazal, M. A., Onaya, T. T. & Craig, W. H., (2005).Determination of solid waste sorption capacity for selected heavy metals in landfills. *Journal of Hazardous Materials*, Vol. B121, pp. 223–232.
31. Bilgili, M. S., Demir, A., Ince, M. & Ozkaya, B. (2007). Metal concentrations of simulated aerobic and anaerobic pilot scale landfill reactors. *Journal of Hazardous Materials,* Vol. 145, pp. 186–194.
32. Olivier, F. & Gourc, J. P. (2007). Hydro-mechanical behavior of Municipal Solid Waste subject to leachate recirculation in a large-scale compression reactor cell. *Waste Management,* Vol. 27, pp. 44–58.