APPLIED TECHNOLOGIES IN MUNICIPAL SOLID WASTE LANDFILL LEACHATE TREATMENT

Huu-Hao Ngo
Faculty of Engineering and Information Technology, School of Civil and Environmental Engineering, University of Technology Sydney, Australia

Wenshan Guo
Faculty of Engineering and Information Technology, School of Civil and Environmental Engineering, University of Technology Sydney, Australia

Wen Xing
Faculty of Engineering and Information Technology, School of Civil and Environmental Engineering, University of Technology Sydney, Australia

Keywords: landfill leachate, conventional treatment technologies, advanced treatment technologies

Contents

Summary

This chapter illustrates the municipal solid waste landfill's characteristics and discharge standard, its pollution problems and environmental impacts, and its typical applied solution technologies. The applied treatment technologies are discussed based on two main catalogues of conventional and advanced technologies. The conventional technologies include: (i) physico-chemical (coagulation-flocculation, chemical

precipitation, activated carbon adsorption, ion exchange, membrane filtration, chemical oxidation etc.); (ii) biological (aerobic or anaerobic conditions, suspended-growth or attached-growth conditions, and fixed-bed or moving-bed conditions). The advanced technologies are introduced to three integration groups of (i) physicochemical, (ii) multi-biological, and (iii) physicochemical-biological processes.

1. Introduction

One of the major pollution problems caused by the municipal solid waste (MSW) landfill is landfill leachate, which is generated as a consequence of precipitation, surface run-off, and infiltration or intrusion of groundwater percolating through a landfill, biochemical processes in waste's cells and the inherent water content of wastes themselves. After a landfill site is closed, a landfill will continue to produce contaminated leachate and this process could last for 30-50 years. Generally, leachate may contain large amounts of organic matter (biodegradable, but also refractory to biodegradation), as well as ammonia-nitrogen, heavy metals (e.g. copper, iron, zinc, lead, manganese etc.), chlorinated organic and inorganic salts (e.g. chloride, sulfate, sodium etc.), which are a great threat to the surrounding soil, groundwater and even surface water (Renou et al., 2008; Robinson, 2005). The composition of landfill leachate is not ubiquitous and varies with different sites and environmental conditions, depending on the nature of the deposited wastes, on soil characteristics, rainfall patterns and on the "age" of the landfill (Iaconi et al., 2006; Park et al., 2001).

The landfill leachate creates the potential to contaminate ground water and surface water supply, and threaten human health when migrating from the landfill and contaminates the surrounding lands and water. With the growth of population and development of the industry, the landfill leachate problem becomes increasingly serious. According to the survey of United States Environmental Protection Agency (USEPA), there are about 55,000 landfills in the USA, approximately 75 percent of which are polluting groundwater (USEPA, 2004). The cases of water polluted by landfill leachate have also been found globally, especially in European countries, Australia and China.

Generally, the best way of controlling the pollution of environment by the landfill leachate is treating leachate to remove the hazardous components before it enters the water systems. The reason is that once the leachate enters the water bodies, it is very expensive and difficult to clean up the contaminated water. There are two leachate management strategies used by modern municipal landfills. These two processes are leachate recirculation and single pass leaching (Scott et al., 1994). The recirculation of leachate (including leachate containment, collection, and recirculation) is appropriate for landfill located in warm areas with low rainfall, and the benefits of this method are simplicity of operation and low operation costs. On the other hand, the single pass leaching strategy is applied to most landfills where the generated leachate is collected and treated to remove most of the contaminants before it is discharged.

Characterization and treatment of landfill leachate has only taken place within the last 40 years. The main applicable methods are physical, chemical and biological. Since it is difficult to obtain satisfactory effluent quality by using anyone of those methods alone, a combination of physical, chemical and biological methods are employed for efficacious treatment of landfill leachate (Kargi and Pamukoglu, 2004a; Uygur et al., 2004). In the physical treatment technologies used for landfill leachate treatment, air-stripping, adsorption and membrane filtration are the major ones. Coagulation-flocculation, chemical precipitation and oxidation are the common chemical leachate treatment methods. Meanwhile, biological treatment technologies consist of aerobic, anoxic and anaerobic processes, which are widely employed for biodegradable contaminants removal from landfill leachate.

2. Leachate Characteristics and its Discharge Standards

2.1 Leachate Characteristics

Landfill leachate consists of a number of complex factors, including solid waste composition, age of the waste, operation of the landfill, hydrogeological conditions in vicinity of the landfill site, rate of the water movement through the waste, landfill temperature, moisture content, pH, landfill chemical and biological activities and seasonal weather variations (Westlake, 1995; McArdle et al., 1988). The production of leachate also varies widely through the successive aerobic, acetogenic, methanogenic and stabilization stages. Table 1 gives the definition of three types of leachates according to landfill age (Renou et al., 2008). The typical chemical concentrations in young and old landfill leachates comparing with sewage and groundwater are also shown in Table 2 (McBean et al., 1995).

Parameter	**Young**	**Intermediate**	**Old**
Age (years)	< 5	5–10	>10
pH	6.5	6.5–7.5	>7.5
COD (mg/L)	>10,000	4,000–10,000	<4,000
BOD5/COD	>0.3	0.1–0.3	<0.1
Organic compounds	80% volatile fat acids (VFA)	5–30% VFA + humic and fulvic acids	Humic and fulvic acids
Heavy metals	Low–medium	Low	Low
Biodegradability	Important	Medium	Low

Table 1 Landfill leachate classification vs. age

Parameter	**Young leachate concentration (mg/L)**	**Old leachate concentration (mg/L)**	**Typical sewage concentration (mg/L)**	**Typical groundwater concentration (mg/L)**
COD	20,000–40,000	500–3,000	350	20
BOD5	10,000–20,000	50–100	250	0
TOC	9,000–15,000	100–1,000	100	5

Volatile fatty acids (as acetic acid)	9,000–25,000	50–100	50	0

Table 2 Typical chemical concentrations in landfill leachate comparing with sewage and groundwater

Landfill / Parameter(mg/L)	LHWMC (NSW)	Olympic Park (NSW)*	Russell Vale (NSW)	Lyndhurst (VIC)	Summary
Age (year)	2-12	6	4	—	—
pH	6.2-8.9	6.59-6.98	8.4	5.3-7.9	5.3-8.9
COD	270-14000	—	218	50-730	50-14000
BOD_5	12-11400	—	46	30-200	6.8-11400
DO	0-4	—	9.9	—	0-9.9
Conductivity(μS/cm)	6000-22000	17700-23100	—	270-22000	240-23100
Temperature (^{o}C)	15-34	—	—	36-38	15-38
SS	25-605	—	8.6	24-2600	8.6-2600
TDS	—	10400-13900	—	270-14000	270-14000
TOC	135-6200	—	—	59-2700	59-6200
TKN	—	—	42.7		0.14-42.7
NO_3^-	—	—	1	<0.05-2.3	<0.05-2.3
NO_2^-	—	—	0.14	<0.05-0.21	<0.05-0.21
N(organic)	—	—		2-70	2-70
NH_3	255-2600	109-242	32.4	1.1-390	1.1-1600
Inorganic PO_4(μg/L)		—	31.5		31.5
P(total)(μg/L)		—	80.6		80.6
Cl^-	40-1190	7200-19800	296	610-6400	40-19800
SO_3^{2-}		—	1.03	0.2-0.75	0.2-1.03
SO_4^{2-}	<5-295	—	195	1.4-130	1.4-295
Alkalinity($CaCO_3$)	—	—	1605	490-4500	490-4500
Ca	—	—	71.7	70-350	70-350
Mg	—	—	30.9	0.74-540	0.74-540
K	400-1200	—	62.3	99-380	62.3-1200
Na	200-1500	—	228	71-3900	71-3900
As	<0.05	0.00001-0.00151	—	0.008-0.07	0.00001-0.07
Ba	<1-22.5	—	—	—	<1-22.5
B	1.3-2.2	—	—	—	1.3-2.2
Cu	<1	0.001-0.005	<0.1	0-0.17	<1
Cd	<0.01-0.02	0.00005-0.0005	<0.05	<0.02	<0.05
Cr	<0.02-1	0-0.01	<0.05	0-0.13	0-0.13
Fe	8.1-235	0.31-9.1	13	0.56-130	0.56-235
Pb	0-0.05	0.0002-0.01	<0.1	0-0.05	<0.1
Mn	<0.05-0.95	—	0.59	0.33-0.51	0.05-1.6
Hg	<0.002	0	—	—	<0.002
Ni	—	—	—	0.07-0.08	0.07-0.08
Se	<0.01	—	—	—	<0.01
Ag	<0.05	—	—	—	<0.05
Zn	0-12	0.037-0.388	0.8	0.34-0.35	0-12
Phenols (total)	0-24	—	—	—	0-24
Toluene	0-1	0.039-3.54	—	—	0-3.54
Xylenes	0-0.5	0.025-1.01	—	—	0-1.01
Benzene	0-0.04	—	—	—	0-0.04
Ethylbenzene	0-0.12	0.014-1.92	—	—	0-1.92

* Data from Sydney Olympic Park landfill, NSW, Australia

Table3. The characteristics of some typical landfill leachate in Australia

Normally, young landfill leachates (the acid-phase landfill, <5 years) contain large amounts of biodegradable organic matter. More than 95% of the dissolved organic carbon (DOC) content of 20,000 mg/L consists of volatile fatty acids, and as little as 1.3% of high molecular weight compounds. In a landfill matures (the methanogenic-phase landfill), the organic fraction in the leachate becomes dominated by refractory (non-biodegradable or humic-like) compounds, and 32% of the DOC content of 2100 mg/L consists of high molecular weight compounds (Wang et al., 2003; Welander et al., 1997; Harsem, 1983). According to the study of Diamadopoulos (1994), the concentration of the organic substances and the ratio of BOD to COD are generally higher during the active stage of decomposition and decrease gradually to less than 0.1 because of the leachate stabilized. Ammonia nitrogen represents the high strength and heavy metals such as copper, iron, zinc, lead, manganese have relatively low concentration. Dissolved solids such as chloride, sulfate, and sodium also present the high level in landfill leachate.

It is known that no two municipal landfills produce the same quality of leachate. Australian landfill leachate contains high strength of ammonia nitrogen (1.1-1600 mg/L), chemical oxygen demand (50-14,000 mg/L), biological oxygen demand (96.8-11,400 mg/L), total dissolved solids (270-14,000 mg/L) and refractory organic matter, which have potentially detrimental to the environment (Scott et al., 2005). Table 3 shows the characteristics of some typical landfill leachates in Australia.

2.2 Leachate Discharge Standards

Currently, the quality of landfill leachate effluent has to comply with increasingly stringent discharge standard. Since there has no legislated landfill leachate discharge standards in Australia, Tables 4 lists the discharge standards of treated wastewater into the aquatic ecosystem (EPA, 2005). Table 5 indicates that several countries and regions have their own leachate discharge standard (Cao et al., 2001; Qzturk et al., 2003; Kurniawan et al., 2006a; Fan et al., 2007; Bohdziewicz et al, 2008a). The removal of organic substances based on total organic carbon (TOC), chemical oxygen demand (COD), biological oxygen demand (BOD) and ammonium from leachate is the usual prerequisite before discharging the leachates into natural waters. Toxicity analysis has confirmed the potential dangers of landfill leachates and the necessity to treat it so as to meet the standards for discharge in receiving waters (Silva et al., 2004; Clément et al., 1997).

Pollutants (mg/L)	**Discharge Limits**	
	Aquatic ecosystem	
	Fresh water	**Marine**

pH	6.5-9	—
TOC	15	10
BOD_5	10	10
DO	>6	>6
Turbidity (NTU)	20	10
SS	20	10
TN	5	5
NH_4-N	0.5	0.2
PO_4-P	0.1	0.1
TP	0.5	0.5
As	0.05	0.05
Cu	0.01	0.01
Cd	0.002	0.002
Cr^{5+}	0.001	0.0044
Fe	1	—
Pb	0.005	0.005
Hg	0.0001	0.0001
Ni	0.15	0.015
Se	0.005	0.07
Ag	0.0001	0.01
Zn	0.05	0.05
Phenols (total)	0.05	0.05
Toluene	0.3	—
Benzene	0.3	0.3
PCBs	0.000001	0.00004
PAHs	0.003	0.003

Table 4 Australian treated wastewater discharge standards

Country Parameter	**UK**	**Hong Kong**	**Vietnam**	**Germany**	**France**	**South Korea**	**Turkey**	**Taiwan**	**Poland**
COD (mg/L)	—	200	100	200	120	50	100	200	125
BOD_5 (mg/L)	60	800	50	20	30	—	50	—	30
SS (mg/L)	—	—	—	—	—	—	100	50	—

NH_4-N (mg/L)	—	5	—	—	5	50	—	—	10
PO_4-P (mg/L)	—	25	6	3	25	—	1.0 (TP)	—	—
Total nitrogen	—	100	60 (TKN)	70	30	150	—	—	—

Table 5 Maximum overseas treated leachate discharge limits

3. Problems and Environmental Impacts of Landfill Leachate

3.1 Organic Matter

Organic matter is one of major pollutants present in landfill leachate. When the leachate with high concentration of organic pollutants enters underground or surface water, organic matter is degraded by respiration of aerobic microorganisms which consume dissolved oxygen (DO). When the water is not able to sustain certain level of DO, the life in the water not can survive. The organic matter can also be degraded by anaerobic microorganisms into some hazardous gas such as CH_4, CO_2 and NH_3, which influence the quality of water severely (Zhang et al., 1999). Organic compounds can be divided into two groups: volatile organic compounds (VOCs) and nonvolatile organic compounds (Scott et al., 2005). Both of them contain carbon-based compounds that are often toxic or carcinogenic. Considering environmental and health effects, dichloromethane, 1,2-dichloroethane and trichloroethene in leachate are the most important organic toxicants in terms of drinking water standard. Dichloromethane, trichloroethene, tetrachloroethene, toluene and PCBs may increase the risk of cancer and may cause some skin problems such as chloracne, rashes and irritation. The health effects of organic toxicants are listed in Table 6. It is difficult to degrade these toxicants using chemical and biological processes within landfill where there is no access for oxygen and sunlight. Moreover, these contaminants cannot be absorbed by soil particles and easily migrate to groundwater beyond the landfill boundaries from leachate.

Organic Compounds	**Health Effect**	**References**
Dichloromethane (DCM)	Short-term exposure – headaches, fatigue, and feeling of drunkenness Exposure to high concentrations – unconsciousness and death Long-term exposure – damage to liver and brain Cancer – lungs, liver and pancreas.	Richardson，1992
1,2-dichloroethane (12-DCE_a)	Short-term exposure-may cause eye problems, headache, feeling of drunkenness, fatigue, central nervous system depression, convulsions, pulmonary oedema, unconsciousness and death. Long-term exposure – damage to the liver, kidneys, lungs and	ATSDR, 1997

	adrenal glands.	
Trichloroethene (TCE_e)	Short-term exposure – beginning with headache, dizziness, and confusion and progressing with increasing exposure to unconsciousness and death. Long-term exposure – damage liver and kidney to leukemia Skin – rushes and liver cancer	Sittig, 1991
Tetrachloroethene (T_eCE_e)	Inhalation – dizziness, headache, sleepiness, confusion, nausea, difficulty in speaking and walking, unconsciousness, and death Skin – irritation	Sittig, 1991
Toluene	Inhalation – fatigue, confusion, headache, dizziness and drowsiness. Ingestion – abdominal spasms Skin – irritation Long-term exposure – liver and kidney damage	Furnell et al., 1989
Hexachlorobenzene	Ingestion – liver disease with associated skin lesions called porphyria cutanea tarda Children – abnormal physical development	ADSTR, 2002
Pentachlorophenol (PeCP)	Short-term exposure – increases in temperature, profuse sweating, and difficulty breathing, even death. Long-term exposure – damage to liver and immune system, damage to the thyroid and reproductive system.	ADSTR, 2001
Aldrin/Dieldrin	Ingestion – convulsions and some died. Long-term exposure – headaches, dizziness, irritability, vomiting, and uncontrolled muscle movements	ADSTR, 2002
Lindane	Short-term exposure – central nervous system stimulation (usually developing within 1 hour), mental/motor impairment, excitation, clonic (intermittent) and tonic (continuous) convulsions, increased respiratory rate and/or failure, pulmonary edema, and dermatitis Long-term exposure – kidney, pancreas, testes, and nasal mucous membrane damage	Ware, 1986
PCBs	Long-term exposure – anemia, damage to liver, stomach, thyroid gland and immune system Skin – chloracne and rashes Cancer – liver and biliary tract	Sittig, 1991

Table 6 Health effects of organic toxicants in landfill leachate

-
-
-

Bibliography

Agdag, O.N. and Sponza, D.T. (2005). Anaerobic /aerobic treatment of municipal landfill leachate in sequential two-stage up-flow anaerobic sludge blanket reactor (UASB)/completely stirred tank reactor (CSTR) systems. *Process Biochemistry*, 40: 895-902. [A comprehensive study on leachate treatment using two combined conventional treatment technologies].

Agency for Toxic Substances and Disease Registry (ATSDR) (2007). Toxicological Profile for Arsenic. Atlanta, GA: U.S. Department of Public Health and Human Services, Public Health Service. [The ATSDR toxicological profile succinctly characterizes the toxicologic and adverse health effects information for Arsenic].

Agency for Toxic Substances and Disease Registry (ATSDR) (2007). Toxicological Profile for Lead. Atlanta, GA: U.S. Department of Health and Human Services, Public Health Service. [The ATSDR toxicological profile succinctly characterizes the toxicologic and adverse health effects information for Lead].

Agency for Toxic Substances and Disease Registry (ATSDR) (2005). Toxicological Profile for Nickel. Atlanta, GA: U.S. Department of Public Health and Human Services, Public Health Service. [The ATSDR toxicological profile succinctly characterizes the toxicologic and adverse health effects information for Nickel].

Agency for Toxic Substances and Disease Registry (ATSDR) (2005). Toxicological profile for Zinc. Atlanta, GA: U.S. Department of Health and Human Services, Public Health Service. [The ATSDR toxicological profile succinctly characterizes the toxicologic and adverse health effects information for Zinc].

Agency for Toxic Substances and Disease Registry (ATSDR) (2004). Toxicological Profile for Cobalt. Atlanta, GA: U.S. Department of Health and Human Services, Public Health Service. [The ATSDR toxicological profile succinctly characterizes the toxicologic and adverse health effects information for Cobalt].

Agency for Toxic Substances and Disease Registry (ATSDR) (2004). Toxicological Profile for Copper. Atlanta, GA: U.S. Department of Health and Human Services, Public Health Service. [The ATSDR toxicological profile succinctly characterizes the toxicologic and adverse health effects information for Copper].

Agency for Toxic Substances and Disease Registry (ATSDR) (2002). Toxicological Profile for Aldrin and Dieldrin. Atlanta, GA: U.S. Department of Health and Human Services, Public Health Service. [The ATSDR toxicological profile succinctly characterizes the toxicologic and adverse health effects information for Aldrin and Dieldrin].

Agency for Toxic Substances and Disease Registry (ATSDR) (2002). Toxicological Profile for Hexachlorobenzene. Atlanta, GA: U.S. Department of Health and Human Services, Public Health Service. [The ATSDR toxicological profile succinctly characterizes the toxicologic and adverse health effects information for Hexachlorobenzene].

Agency for Toxic Substances and Disease Registry (ATSDR) (2001). Toxicological Profile for Pentachlorophenol. Atlanta, GA: U.S. Department of Health and Human Services, Public Health Service. [The ATSDR toxicological profile succinctly characterizes the toxicologic and adverse health effects information for Pentachlorophenol].

Agency for Toxic Substances and Disease Registry (ATSDR) (2000). Toxicological profile for Chromium. Atlanta, GA: U.S. Department of Health and Human Services, Public Health Service. [The ATSDR toxicological profile succinctly characterizes the toxicologic and adverse health effects information for Chromium].

Agency for Toxic Substances and Disease Registry (ATSDR) (1999). Toxicological Profile for Cadmium. Atlanta, GA: U.S. Department of Health and Human Services, Public Health Service. [The ATSDR toxicological profile succinctly characterizes the toxicologic and adverse health effects information for Cadmium].

Agency for Toxic Substances and Disease Registry (ATSDR) (1999). Toxicological Profile for Mercury. Atlanta, GA: U.S. Department of Health and Human Services, Public Health Service. [The ATSDR toxicological profile succinctly characterizes the toxicologic and adverse health effects information for Mercury].

Agency for Toxic Substances and Disease Registry (ATSDR) (1997). Toxicological Profile for 1, 2-Dichloroethane. Atlanta, GA: U.S. Department of Health and Human Services, Public Health Service. [The ATSDR toxicological profile succinctly characterizes the toxicologic and adverse health effects information for 1, 2-Dichloroethane].

Aghamohammadi, N., Aziz, H.A., Isa, M. H., Zinatizadeh, A.A. (2007). Powered activated carbon augmented activated sludge process for treatment of semi-aerobic landfill leachate using response surface methodology. *Bioresourse Technology*, 98: 3570-3578. [The paper discusses the specific treatment using PAC adsorption technology].

Ahn, D.H., Chung, Y.C., Chang, W.S. (2002a). Use of coagulant and Zeolite to enhance the biological treatment efficiency of high ammonia leachate. *Journal of Environmental Science and Health,* A37 (2): 163-173. [This study shows the combined coagulation-adsorption process in treating leachate with high ammonia concentration].

Ahn, W.Y., Kang, M.S., Yim, S.K., Choi, K.H. (2002b). Advanced landfill leachate treatment using an integrated membrane process. *Desalination*, 149: 109-114. [This presents approaches to improve treatment efficiency by using integrated membrane process that is composed of membrane bioreactor (MBR) and reverse osmosis (RO) process].

Amokrane, A., Comel, C., Veron, J. (1997). Landfill leachates pretreatment by coagulation-flocculation. *Water Research*, 31: 2775-2782. [In this work, coagulation-flocculation is examined and optimized as an appropriate reverse osmosis pretreatment of stabilized landfill leachates].

Aziz, H.A., Adlan, M.N., Zahari, M.S.M., Alias, S. (2004). Removal of ammonia-nitrogen (NH_3-N) from municipal solid waste leachate by using activated carbon and limestone. *Waste Management & Research,* 22: 371-375. [This is a study reporting on the application of adsorption technology for leachate treatment].

Bila, D.M., Montalvao, A.F., Silva, A.C., Dezotti, M. (2005). Ozonation of a landfill leachate: evaluation of toxicity removal and biodegradability improvement. *Journal of Hazardous Materials*, 117:235-242. [This work developed a sequence of processes, namely coagulation/flocculation, followed by ozonation and biological treatment, for treating a leachate with very peculiar characteristics].

Bodzek, M., Surmacz-Gorska, J., Hung, Y.T., (2004). Treatment of landfill leachate. In: *Handbook of Industrial and Hazardous Wastes Treatment*, Wang, L.K., Hung, Y.T., Lo, H.H. and Yapijakis, C. (ed.), Ch 28, 2nd Edition, Marcel Dekker, NY, USA. [This book chapter discussed different methods guaranteeing proper environmental protection about water quality and environmental standards in worldwide leachate treatment].

Bohdziewicz, J., Neczaj, E., Kwarciak, A. (2008a). Landfill leachate treatment by means of anaerobic membrane bioreactor. *Desalination*, 221: 559-565. [The study was undertaken to examine feasibility of biological treating of landfill leachate in anaerobic submerged membrane bioreactor].

Bohdziewicz, J. and Kwarciak, A. (2008b). The application of hybrid system UASB reactor-RO in landfill leachate treatment. *Desalination*, 222: 128-134. [The aim of the paper was to study landfill leachate treatment efficiency during fermentation process in UASB reactor and post-treatment in RO process].

Bohdziewicz, J., Bodzek, M., Górska, J. (2001). Application of pressure-driven membrane techniques to biological treatment of landfill leachate. *Process Biochemistry*, 36: 641-646. [This investigation aims to define the efficiency of treatment of landfill leachate in the systems combining the following processes: biological, chemical oxidation and pressure-driven membrane techniques].

Calli, B., Mertoglu, B., Inanc, B. (2005). Landfill leachate management in Istanbul: application and alternative. *Chemosphere*, 59: 819-829. [This paper evaluated the feasibility of treatment for leachate using different treatment alternatives].

Canziani, R., Emondi, V., Garavaglia, M., Malpei, F., Pasinetti, E., Buttiglieri, G. (2006). Effect of oxygen concentration on biological nitrification and microbial kinetics in a cross-flow membrane bioreactor (MBR) and moving-bed biofilm reactor (MBBR) treating old landfill leachate. *Journal of Membrane Science*, 286: 202-212. [This research was to achieve complete conversion of ammonium to nitrite in an MBR with high sludge retention time and by controlling T, DO and pH].

Cao, H.T., Nguyen, H.D., Nguyen, Q.H., Truong, L.P., Nguyen, H.K., Duong, D.T., Nguyen, T.V., Nguyen, A.T., Nguyen T.D. (2001). In Core university program, Study on treatment of the leachate from landfill site Namson, Socson, Hanoi, 154-162, Japan. [This report presents approaches to the study on landfill leachate treatment technologies].

Chen, S., Sun, D., Chung, J.S. (2008). Simultaneous removal of COD and ammonium from landfill leachate using an anaerobic moving-bed biofilm reactor system. *Waste Management*, 28(2): 339-346. [The performance of a moving-bed biofilm reactor (MBBR) system with an anaerobic–aerobic arrangement was investigated to treat landfill leachate for simultaneous removal of COD and ammonium].

Chianese, A., Ranauro, R., Verdone, N. (1999). Treatment of landfill leachate by reverse osmosis. *Water Research*, 33(3): 647-652. [This paper deals with an experimental study describing the treatment of landfill leachate by means of a pilot-scale reverse osmosis unit].

Clément, B., Janssen, R.C., Le Dû-Delepierre, A. (1997). Estimation of the hazard of landfills through toxicity testing of leachates. *Chemosphere*, 35: 2783–2796. [This paper revealed the hazardousness and toxicity of landfill leachate].

Diamadopoulos, E. (1994). Characterization and treatment of recirculation-stabilized leachate. *Water Research*, 28(22): 2439-2445. [The objectives of this work were to characterize leachate stabilized by recirculation and to investigate physico-chemical methods for the appropriate treatment].

EPA (Environment Protection Authority) (2005). Environment Protection (Water Quality) Policy, Version 3. South Australia. [The document lists the discharge water quality standards for treated wastewater].

Fan, H.J., Chen, I. W., Lee, M.H., Chiu, T. (2007). Using FeGAC/H_2O_2 process for landfill leachate treatment. *Chemosphere*, 67:1647-1652. [This study developed an alternative oxidation process (iron oxide coated granular activated carbon (FeGAC)/H2O2 for the removal of humic substance in municipal landfill leachate).

Furnell, B.S. (1989). *Vogel's Textbook of Practical Organic Chemistry*, 5th edition, Longman/Wiley, New

York. [A comprehensive textbook about practical organic chemistry].

Galvez, A., Zamorano, M., Ramos, A., Hontoria, E. (2005). Coagulation-flocculation pretreatment of a partially stabilized leachate from a sanitary landfill site at Alhendin (Granada, Southern Spain). *Journal of Environmental Science and Health,* 40: 1741-1751. [This study presents the examination of coagulation–flocculation process efficiency as a pretreatment to treat stabilized leachate].

García, H., Rico, J.L., García, P.A. (1996). Comparison of anaerobic treatment of leachates from an urban-solid-waste landfill at ambient temperature and at 35 ºC. *Bioresource Technology*, 58: 273-277. [This research was to study the removal efficiency of organic pollutants in leachates under different loading conditions and at different temperatures by using a laboratory-scale UASB reactor].

Gourdon, R., Comel, C., Vermande, P., Veron, J. (1989). Fractionation of the organic matter of landfill leachate before and after aerobic or anaerobic biological treatment. *Water Research,* 23(2): 167-173. [This paper relates a comparative study of the amount and composition of the organic matter resistant to an aerobic or an anaerobic biological treatment of a landfill leachate devoid of volatile fatty acids].

Griffith, E.J., Beeton, A., Spencer, J.M., Mitchell, D.T. (1973). *Environmental phosphorus handbook.* Wiley-Interscience, New York, 718. [A comprehensive handbook about the environmental impacts of phosphorus].

Harsem, J. (1983). Identification of organic compounds in leachate from a waste tip, *Water Research*, 17, 699–705. [In this paper, 45 organic compounds have been identified in leachates from a Swedish municipal landfill].

He, R., Liu, X.W., Zhang, Z.J., Shen, D.S. (2007). Characteristics of the bioreactor landfill system using an anaerobic-aerobic process for nitrogen removal. *Bioresourse technology*, 98: 2526-2532. [A sequential upflow anaerobic sludge blanket (UASB) and air-lift loop sludge blanket (ALSB) treatment was introduced into leachate recirculation to remove organic matter and ammonia from leachate].

Hem, J.D. (1985). Study and Interpretation of the Chemical Characteristics of Natural Water. *Water Supply,* 3: 2254. [A comprehensive study on the chemicals presented in natural water].

Iaconi, C.D., Ramadori, R., Lopez, A. (2006). Combined biological and chemical degradation for treating a mature municipal landfill leachate. *Biochemical Engineering Journal*, 31:118-124. [A laboratory scale investigation aimed at evaluating the effectiveness of mature municipal landfill leachate treatment by a biological stage followed by a chemical oxidation].

Im, J.H., Woo, H.J., Choi, M.W., Han, K.B., Kim C.W. (2001). Simultaneous organic and nitrogen removal from municipal landfill leachate using an anaerobic–aerobic system. *Water Research*, 35: 2403–2410. [The performance of a moving-bed biofilm reactor (MBBR) system with an anaerobic–aerobic arrangement was investigated to treat landfill leachate for simultaneous removal of COD and ammonium].

Kabdasli, I., Tunay, O., Ozturk, I., Yilmaz, S., Arikan, O. (2000). Ammonia removal from young landfill leachate by magnesium ammonia phosphate precipitation and air stripping. *Water Science and Technology*, 41(1): 237-240. [The results of ammonia stripping and MAP precipitation treatability studies applied to young leachates was given and discussed in this study].

Kargi, F., Pamukoglu, M.Y. (2004a). Repeated fed-batch biological treatment of pre-treated landfill leachate by powdered activated carbon addition. *Enzyme and Microbial Technology,* 34, 422-428. [This paper shows the treatment efficiency of the repeated fed-batch biological process as a post-treatment to adsorption process].

Kargi, F. and Pamukoglu, M.Y. (2004b). Adsorbent supplemented biological treatment of pre-treated landfill leachate by fed-batch operation. *Bioresource Technology*, 94: 285-291. [This study investigated and compared the adsorption performances of powdered activated carbon (PAC) and powdered zeolite (PZ) in biological treatment of pretreated landfill leachate].

Kennedy, K.J. and Lentz, E.M. (2000). Treatment of landfill leachate using sequencing batch and continuous flow upflow anaerobic sludge blanket. *Water Research*, 34(14): 3640-3656. [A detailed study on treatment of municipal landfill leachate using sequencing batch and continuous flow upflow anaerobic sludge blanket reactors].

Kettunen, R.H. and Rintala J.A. (1998). Performance of an on-site UASB reactor treating leachate at low temperature. *Water Research*, 32(3): 537-546. [A study about the treatability of UASB reactor treating leachate at low temperature].

Kettunen, R.H., Hoililjoki, T.H., Rintala, J.A. (1996). Anaerobic and sequential anaerobic-aerobic treatments of municipal landfill leachates at low temperatures. *Bioresource Technology*, 58: 31-40. [This study was to determine the suitability of anaerobic and sequential anaerobic-aerobic processes for the treatment of municipal landfill leachate at low temperatures].

Kurniawan, T.A., Lo, W.H., Chan, G.Y. (2006a). Physico-chemical treatment for removal of recalcitrant contaminants from landfill leachate. *Journal of Hazardous Materials*, B129: 80-100. [The technical applicability and treatment performance of physico-chemical techniques for landfill leachate are reviewed in this paper].

Kurniawan, T.A., Lo, W.H., Chan, G.Y.S. (2006b). Degradation of recalcitrant compounds from stabilized landfill leachate using a combination of ozone-GAC adsorption treatment. *Journal of Hazardous Materials*, B137: 443-455. [The investigation on performances of ozonation alone and/or its combination with granular activated carbon (GAC) adsorption for raw leachate treatment].

Laitinen, N., Luonsi, A., Vilen, J. (2006). Landfill leachate treatment with sequencing batch reactor and membrane bioreactor. *Desalination*, 86-91. [The study on the treatability of combined sequencing batch reactor and MBR treating landfill leachate].

Lei, Y., Shen, Z., Huang, R., Wang, W. (2007). Treatment of landfill leachate by combined aged-refuse bioreactor and electro-oxidation. *Water Research*, 41: 2417-2426. [Combined aged-refuse bioreactor and electro-oxidation was investigated to treat leachate].

Li, X.Z., Zhao, Q.L., Hao, X.D. (1999). Ammonia removal from landfill leachate by Chemical precipitation. *Waste Management*, 19: 409-415. [The study focuses on ammonia removal by chemical precipitation].

Liang, Z. and Liu, J. (2008). Landfill leachate treatment with a novel process: anaerobic ammonium oxidation (Anammox) combined with soil infiltration system. *Journal of Hazardous Materials*, 151:202-212. [A novel combined process was proposed to treat municipal landfill leachate with high concentrations of ammonium and organics].

Lin, C. Y., Chang, F.Y., Chang, C.H. (2000). Co-digestion of leachate with septage using a UASB reactor. *Bioresource Technology*, 73:175-178. [Treatment of landfill leachate using anaerobic biological process].

Lin, S.H. and Wu, C.L. (1995). Removal of nitrogenous compounds from aqueous solution by ozonation and ion exchange. *Water Research*, 30(8): 1851-1857. [The investigation of the ammonia, nitrite and nitrate removal from aqueous solution using ozonation and ion exchange].

Linde, K. and Jonsson, A. (1995). Nanofiltration of salt solution and landfill leachate. *Desalination*, 103:223-232. [This research investigated the performance of nanofiltration in leachate treatment compared with other membrane processes].

Majone, M., Papini, M.R., Rolle, E. (1997). Influence of metal speciation in landfill leachate on kaolinite sorption. *Water Research*, 32(1): 882-890. [The paper shows the sorption of Pb, Cd, Ni and Cu onto kaolinite from a landfill leachate].

Marttinen, S.K., Kettunen, R.H., Sormunen, K.M., Soimasuo, R.M., Rintala, J.A. (2002). Screening of physico-chemical methods for removal of organic material, nitrogen and toxicity from low strength landfill leachates. *Chemosphere*, 46: 851-858. [This study evaluated the feasibility of nanofiltration and air stripping for treatment and ozonation for pretreatment of low strength municipal landfill leachates].

McArdle, J.L., Arozarena, M.M., Gallagher, W.E. (1988). *Treatment of hazardous waste leachate: unit operation and cost.* Noyes Data Corporation, New Jersey, USA. [A comprehensive book about treating hazardous compounds present in landfill leachate].

McBean, E.A., Rovers, F.A., Farquhar, G.J. (1995). Solid waste landfill engineering and design, Prentice Hall PTR, New Jersey, USA. [A comprehensive book about landfill design, landfilling and environmental monitoring].

Meagher, D. (1991). *Macmillan Dictionary of the Australian Environment*, Macmillan Education Australia Pty Ltd. [The guidebook about the characteristics of chemical and their effects on environment and health].

Monje-Ramirez, I., Orta de Velasquez, M.T. (2004). Removal and transformation of recalcitrant organic matter from stabilized saline landfill leachates by coagulation–ozonation coupling processes, *Water Research*, 38: 2359-2367. [The evaluation of coagulation–ozonation coupling processes as a treatment system for saline sanitary landfill leachates, in order to remove and transform recalcitrant organic matter].

Morawe, B., Ramteke, D.S., Vogelpohl, A. (1995). Activated carbon column performance studies of biologically treated landfill leachate. *Chemical Engineering and Processing*, 34: 299-303. [The research shows a complex interaction of adsorption and desorption between the lower and higher molecular weight components of the leachate].

Neczaj,E., Kacprzak,M., Kamizela,T., Lach,J., Okoniewska,E. (2008). Sequencing batch reactor system for the co-treatment of landfill leachate and dairy wastewater, *Desalination*, 222:404-409. [Two aerobic SBRs were investigated to co-treat landfill leachate and the wastewater from industrial milk factory].

Neczaj, E., Okoniewska, E., Kacprzak, M. (2005). Treatment of landfill leachate by sequencing batch reactor. *Desalination*, 357-362. [The effectiveness of applying ultrasound field for enhancement of biological treatability of leachates using SBR].

Ntampou, X., Zouboulis, A.I., Samaras, P. (2006). Appropriate combination of physico-chmical methods (coagulation/ flocculation and ozonation) for the efficient treatment of landfill leachates. *Chemosphere*, 62: 722-730. [An integrated technique consisted of ozonation and coagulation/flocculation processes was studied, aiming to provide an efficient method for the treatment of stabilized/biologically pre-treated leachates].

Otal, E., Vilches, L.F., Moreno, N., Querol, X., Vale, J., Fernandez-Pereira, C. (2005). Application of zeolitised coal fly ashes to the depuration of liquid wastes, *Fuel*, 84: 1440-1446. [The application of some zeolitised fly ashes and synthetic zeolites to the decontamination of the leachate].

Ozturk, I., Altinbas, M. Koyuncu, I., Arikan, O., Gomec-Yangin, C. (2003). Advanced physico-chemical treatment experience on young municipal landfill leachates. *Waster Management*, 23: 441-446. [Membrane Filtration (UF+RO), Struvite (MAP) precipitation and ammonia stripping alternatives were studied on biologically pre-treated Landfill Leachate].

Parawira, W., Murto, M., Zvauya, R., Mattiasson, B. (2006). Comparative performance of a UASB reactor and an anaerobic packed-bed reactor when treating potato waste leachate. *Renewable Energy*, 31: 893-903. [The performance comparison of two anaerobic bioreactors in treating food waste leachate].

Park, S., Choi, K.S., Joe, K.S., Kim, W.H., Kim, H.S. (2001). Variations of landfill leachate's properties in conjunction with the treatment process. *Environmental Technology*, 22, 639–645. [This paper discussed landfill leachates with different ages and their proper treatment methods].

Peters, T.A. Purification of landfill leachate with reverse osmosis and nanofiltration. *Desalination*, 199: 289-293. [A research review about leachate treatment using RO and NF].

Pirbazari, M., Ravindran, V., Badriyha, B.N., Kim, S. (1996). Hybrid membrane filtration process for leachate treatment. *Water Research*, 30(11): 2691-2706. [The study exhibits a hybrid technology known as the ultrafiltration-biologically active carbon (UF-BAC) process is found to be highly efficient for treatment of landfill leachates].

Rautenbach, R., Vossenkaul, K., Linn, T., Katz, T. (1996). Waste water treatment by membrane process-new development in ultrafiltration, nanofiltration and reverse osmosis. *Desalination*, 108: 247-253. [A review on membrane technologies on treating wastewater].

Renou, S., Givaudan, J.G., Poulain, S., Dirassouyan, F., Moulin, P. (2008). Landfill leachate treatment: Review and opportunity. *Journal of Hazardous Materials*, 150, 468–493. [A comprehensive review about up-dated technologies on landfill leachate treatment].

Richardson, M. (1992). *Dictionary of Substances and their Effects*, Royal Society of Chemistry, Clays Ltd, England. [A guidebook about the characteristics of toxic substances and their impacts on environment and human health].

Rivas, F.J., Beltran, F., Gimeno, O., Acedo, B., Carvalho, F. (2003). Stabilized leachates: ozonation-activated carbon treatment and kinetics. *Water Research*, 37: 4823-4834. [This work is to assess the potential of a chemical (ozone)—physical (adsorption) integrated leachate treatment as a complete treatment or as a pretreatment to render the effluent more suitable for a final polishing biodegradation].

Robinson, A. H. (2005). Landfill leachate treatment. *Membrane Technology*, June, 6-12. [An article about current technologies on landfill leachate treatment].

Rodríguez, J., Castrillón, L., Marañón, E., Sastre, H., Fernández, E. (2004). Removal of non-biodegradable organic matter from landfill leachates by adsorption. *Water Research*, 38: 3297-3303. [This paper presents the research work on decreasing pollutant load of leachate using adsorption processes].

Schaep J., Van Der Bruggen, B., Vandecasteele, C., Wilms, D. (1998). Influence of ion size and charge in nanofiltration. *Separation Purification Technology*, 14: 155-162. [A study about ion charge effects on membrane fouling].

Scott, J., Beydoun, D., Amal, R., Low, G., Cattle, J. (2005). Landfill management, leachate generation, and leach testing of solid wastes in Australia and overseas. *Critical Review in Environmental Science and Technology*, 35: 239-332. [A critical review about landfill site management, postclosure care and environmental monitoring].

Scott, J.E. (1994). *Designing constructed wetland to treat landfill leachate.* Thesis (Bachelor of Applied Science), University of Western Sydney, Australia. [A thesis about landfill leachate treatment using constructed wetland].

Silva, A.C., Dezotti, M., Sant'Anna Jr., G.L. (2004). Treatment and detoxication of a sanitary landfill leachate. *Chemosphere*, 55, 207–214. [In this study, leachate was characterized and submitted to coagulation and flocculation treatment followed by ozonation and ammonia stripping].

Sittig, M. (1991). *Handbook of Toxic and Hazardous Chemicals and Carcinogens*, 3rd edition, Noyes Publications, USA. [A comprehensive handbook about the characteristics of hazardous substances and their impacts on human health].

Tatsi, A.A., Zouboulis, A.I., Matis, K.A., Samaras, P. (2003). Coagulation-flocculation pretreatment of sanitary landfill leachate. *Chemosphere,* 53: 737-744. [The purpose of this study were the examination of coagulation–precipitation process efficiency for the treatment of both fresh and partially stabilized leachates, especially in terms of organic matter and solids removal].

Tchobanoglous, G., Burton, F.L. (1991). *Wastewater engineering: treatment, disposal, and reuse,* Metcalf & Eddy, Inc. New York. [A prestigious book on wastewater treatment for civil and environmental engineering majors and presents information on the current state of technology and regulation].

Tizaoui, C., Bouselmi, L., Mansouri, L. and Ghrabi, A. (2007). Landfill leachate treatment with ozone and ozone/hydrogen peroxide systems. *Journal of Hazardous Materials*, 140:316-324. [This study was carried out in order to investigate the treatment of landfill leachate using zone-based processes].

Trebouet, D., Schlumpt, J.P., Jaouen, P., Quemeneur, F. (2001). Stabilized landfill leachate treatment by combined physicochemical-nanofiltration process. *Water Research,* 35(12): 2935-2942. [This research tested several pretreatments to increase nanofiltration performances in treating leachate and to estimate the influence of humic-type substances on membrane fouling].

Tsilogeorgis, J., Zouboulis, Samaras, P., Zamboulis, D. (2008). Application of a membrane sequencing batch reactor for landfill leachate treatment. *Desalination*, 221: 483-493. [This study assessed the performance of a bench-scale MSBR fed with “mature” landfill leachate, containing recalcitrant organic compounds as well as relatively high levels of ammonium nitrogen.].

USEPA (U.S. Environmental Protection Agent) (2004). RCRA environmental progress report, 2004 update, office of solid waste. [A report about solid waste minimization and pollution control].

Ushikoshi, K., Kibayashi, T., Uematsu, K., Toji, A., Kojima, D., Matsumoto, K. (2002). Leachate treatment by the reverse osmosis system. *Desalination,* 150: 121-129. [This paper discussed the performance of RO in treating leachate].

Uygur, A. and Kargi, F. (2004). Biological nutrient removal from pre-treated landfill leachate in a sequencing batch reactor. *Journal of Environmental Management,* 71: 9-14. [Nutrient removal from pre-treated leachate was studied using a lab-scale sequencing batch reactor (SBR)].

Wang, F., Smith, D.W., El-Din, M.G. (2003). Application of advanced oxidation methods for landfill leachate treatment, *Journal of Environmental Engineering and Science*, 2, 413–427. [A review about applying different advanced oxidation technologies for landfill leachate treatment].

Ware, G.W. (1986). *Fundamentals of Pesticides: A Self-Instruction Guide*. Thomson Publications, Fresno, CA, USA, pp 6-2. [A guidebook about theory and environmental impacts of pesticides].

Welander, U., Henryson, T., Welander, T. (1997). Nitrification of landfill leachate using suspended-carrier biofilm technology, *Water Research,* 31, 2351–2355. [Attached growth biofilm was used to remove ammonia present in landfill leachate].

Westlake, K. (1995). Landfill waste pollution and control, Albion publishing limited, England, UK. [A comprehensive book about landfill engineering and pollution control].

Yangin, C., Yilmaz, S., Altinbas, M., Ozturk, I. (2002). A new process for the combined treatment of municipal wastewater and landfill leachates in coastal areas. *Water Science and Technology,* 46(8): 111-118. [In this study, application of anaerobic pre-treatment prior to MAP precipitation was considered as a sustainable treatment process comparable to conventional aerobic treatment].

Yoon, J., Cho, S., Cho, Y., Kim, S. (1998). The characteristics of coagulation of Fenton reaction in the removal of landfill leachate organics. *Water Science and Technology,* 38: 209-214. [Organics characteristics were discussed after using Fenton treating leachate].

Zhang, Z.J., Lin, R.C., Jin, R.L. (1999). *Waste water engineering*, Architecture and Industry Publishing, China. [A comprehensive book describes the technological and theoretical issues on wastewater treatment].

Biographical Sketches

Huu Hao Ngo is an academic and senior environmental research engineer with more than twenty five years' professional experience in Australia and in Asian countries. He is now working as Associate Professor of Environmental Engineering and Manager, in-charge of Environmental Engineering R & D Laboratory, School of Civil and Environmental Engineering at University of Technology, Sydney (UTS). He is also serving as a core member (Team Leader of advanced water and wastewater treatment materials based technology group and Project Investigation of membrane based technology in the theme of Urban Water Management) of the Institute of Water and Environmental Resource Management at UTS. Assoc. Prof. Ngo is internationally known for his activities in the development of innovative water, wastewater treatment and recycling technologies, and is a recognized authority on the flocculation and filtration process, biofiltration and membrane hybrid technology. He has been involved in more than 50 research projects and published more than 200 technical papers including two books and several book chapters. He is also a reviewer for more than 20 international journals.

Wenshan Guo is working as UTS Chancellor's Postdoctoral Research Fellow and her research focus is on the innovative water and wastewater treatment and reuse technologies. Her expertise and practical experience cover the areas of water and wastewater engineering such as membrane technologies (e.g. membrane bioreactor, microfiltration, membrane hybrid system, and PAC-submerged membrane bioreactor etc.), advanced biological wastewater treatment technologies (e.g. suspended growth reactors and attached growth reactors), and physical/chemical separation technologies as pretreatment or post-treatment (e.g. adsorption, column, and flocculation). She also has strong ability to work in solid waste management, life cycle assessment, and desalination.

Wen Xing is working as Technical and Research Assistant in the Environmental Engineering R & D Laboratory at University of Technology. She is also a PhD student in Environmental Engineering.