

Chapter 11

Management of Municipal Solid Waste Landfill Leachate: A Global Environmental Issue

Meththika Vithanage, S.S.R.M.D.H.R. Wijesekara, A. R. Siriwardana,
Soniya S. Mayakaduwa and Yong Sik Ok

Abstract Landfills are one of the most historical and ordinary methods of waste disposal and still remain in many parts of the world. Landfill leachate from open dumpsites has become a crucial environmental issue. Still, the predominant waste disposal method in many developing countries is open dumping, which leads to the generation of significant amounts of leachate mostly to nearby water bodies. Landfill leachate treatment is not an easy task, specifically because of its uniqueness depending on climate, culture, age of the dumpsite, and waste characteristics. Acetogenic leachate characteristics are extremely variable and difficult to predict. However, landfill leachate in the methanogenic phase possesses quite stable characteristics. Herein, we report qualitative and quantitative data on landfill leachate from different parts of the world and discuss the best management practices. In addition, we provide a case study on assessing the physiochemical characteristics of landfill leachate generated from a municipal solid waste dumpsite in Sri Lanka. Overall, landfill leachate poses a risk to the environment and effective leachate management is vital to avoid environmental deterioration.

Keywords Municipal solid waste · Methanogen · Acetogen · Organic carbon · Nitrate · Phosphate

Yong Sik Ok (✉) · M. Vithanage
Korea Biochar Research Center,
Kangwon National University, 200-701 Chuncheon, Korea
e-mail: soilok@kangwon.ac.kr

Yong Sik Ok
Department of Renewable Resources, University of Alberta, Edmonton, Canada

M. Vithanage · S.S.R.M.D.H.R. Wijesekara · S. S. Mayakaduwa
Chemical and Environmental Systems Modeling Research Group,
Institute of Fundamental Studies, Kandy, Sri Lanka

A. R. Siriwardana
Postgraduate Institute of Science, University of Peradeniya, Peradeniya, Sri Lanka

A. Malik et al. (eds.), *Environmental Deterioration and Human Health*,
DOI 10.1007/978-94-007-7890-0_11, © Springer Science+Business Media Dordrecht 2014

11.1 Introduction

11.1.1 *Municipal Solid Waste*

Municipal solid waste (MSW), commonly known as trash or garbage, not only contains household or domestic waste but can also contain commercial and industrial waste with the exception of industrial hazardous waste that is collected through community sanitation services. Industrial hazardous waste (e.g., radioactive and pharmaceutical waste) is excluded from municipal waste because it is typically treated separately based on environmental regulations. In many countries, MSW is generated by three main sources: (1) domestic solid waste (from households and public areas, including waste collected from residential buildings, litter bins, streets, marine areas, and country parks); (2) commercial solid waste (from shops, restaurants, hotels, offices, and markets in private housing estates); and (3) industrial solid waste (industries, but does not include construction and demolition waste, chemical waste, or other special waste). MSW can further be grouped into five different categories (Fig. 11.1) and various techniques have been developed and practiced for MSW management worldwide, such as incineration, anaerobic reactors, and gasification (Kılıç, et al. 2007). However, MSW finally ends up in landfills in most cases.

11.1.2 *MSW Landfilling*

Although there are a number of different ways to dispose of MSW, the first and most well-known method is landfilling. Landfills are discrete, specially created, and excavated areas, so MSW can be put in these areas with little or no harm to the natural environment through pollution. Table 11.1 shows the general characteristics and the major differences in the main land disposal facilities (Training Module 2005). A number of significant characteristics are given in detail in the following:

1. *Open dumps* are particularly practiced in the developing countries. An open dumpsite is a land disposal site where solid wastes are disposed of in a manner that does not protect the environment, is susceptible to open burning, and is exposed to the elements to spread disease vectors (Joseph et al. 2002). Any available vacant area with government ownership is the basic consideration for an open dumpsite and no environmental guidelines are considered. Open dumps are unplanned heaps of uncovered wastes, often burned (many open dumps operators set fire to the MSW at the dumpsite to reduce the waste and increase disposal area at the site) and surrounded by pools of stagnated polluted water, rat, and fly infestations with domestic animals roaming freely and families of scavengers picking through the wastes (Fig. 11.2). Open dumpsites are swamp/marshy lands or low-lying areas where the MSW is being used for reclamation. This type of landfill requires the least development and operational costs and is prevalent in

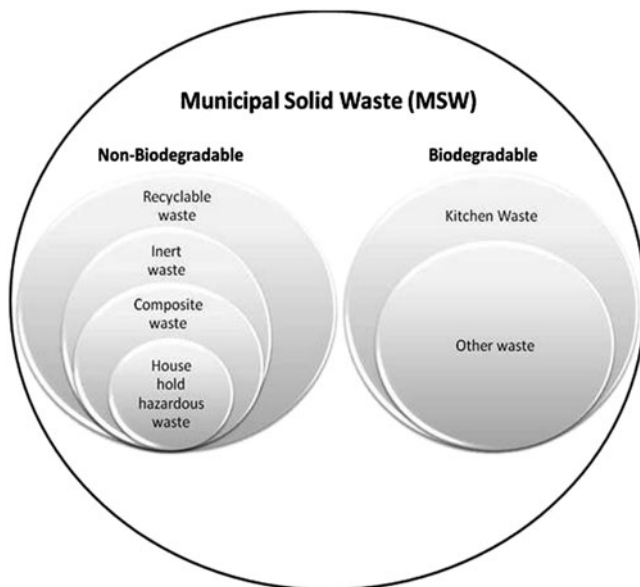


Fig. 11.1 Five different types of MSW in the environment

developing countries, in particular, where sanitary and engineered landfills are now a public health and environmental concern.

2. *Controlled dumps* are the first level of improvement from open dumps (Joseph et al. 2005). Controlled dumpsites are designed to eliminate problems associated with open MSW dumpsites through operational and management aspects rather than high-cost engineering applications. Hydrogeologic conditions are considered for site selection. In addition, several steps are considered compared to open dumping. For example, disposal only occurs at designated areas with planned capacity and where leachate/landfill gas is partially managed. Moreover, drainage and surface water control along the periphery of the site and covering the waste are implemented regularly in controlled dumps to prevent leachate- and landfill gas-related pollution. However, the practice of controlled dumping should be adopted in accordance with other modern waste management strategies.
3. *Engineered landfills* protect the environment and prevent pollutants from entering the soil and possibly polluting ground water in one of two ways. An engineered landfill uses clay or polythene liners High-density polyethylene (HDPE) liners and landfill covers to obstruct pollutants from leaving the landfill (Hartz and Ham 1983). This may reduce the risk of environmental pollution through groundwater and soil contamination and air pollution. However, most dumpsites in developing countries do not have a liner at the base or a top cover for protecting possible water and ground contamination by the leachate (Rafizul and Alamgir 2012).

Table 11.1 Summary of the general characteristics for different type of land disposal facilities around the world. (Source: Joseph et al. 2002 Training Module (2005))

Type	General measures	Engineering measures	Leachate management	Landfill gas management	Operation measures
Open dump	Unplanned, often improperly sited, site capacity is not known, no cell planning	None	Unrestricted contaminant release	None	Few, scavenging, no compaction of waste, and no record keeping
Controlled dump	Hydrogeologic conditions considered, planned capacity, and no cell planning	None	Unrestricted contaminant release	None	Registration and placement, compaction of waste in some cases, basic record keeping
Engineered landfill	Site chosen is based on environmental, community and cost factors planned capacity	Infrastructure and liner in place	Contaminant and some level of leachate management	Passive ventilation or flaring	Registration and placement/compaction of waste; uses daily soil cover
Sanitary landfill	Site chosen is based on environmental, community and cost factors, planned capacity, and cell planning	Proper siting, Infrastructure and liner and leachate treatment in place	Contaminant and leachate treatment (often biological and physico-chemical treatment)	Flaring	Registration and placement/compaction of waste; uses daily soil cover, measures for final top cover, waste compaction, and complete record keeping
Controlled contaminant release landfill	Site chosen is based on environmental, community and cost factors, and planned capacity	Proper siting, infrastructure, with low permeability liner in place, and potentially low permeability final top cover	Controlled release of leachate in to the environment, based on assessment and proper siting	Flaring or passive ventilation through top cover	Registration and placement/compaction of waste; uses daily soil cover, and measures for final top cover
Landfill bioreactor	Site chosen is based on environmental, community and cost factors, and planned capacity	Proper siting, Infrastructure and liner and leachate circulation/generation system	Controlled recirculation of leachate for enhanced degradation and stabilization of waste and leachate	Landfill gas recovery	Registration and placement/compaction/daily cover/closure/mining and material recovery



Fig. 11.2 Uncontrolled scavenging activities and domestic animals roaming on open dumps are common sights in developing countries, which lead to many environmental issues

4. *Sanitary landfills* comprise a series of advanced measures in design, construction, operating, and post-closure steps to have minimum environmental impact. Hence, this technique requires a substantial financial resource compared to other landfilling methods. However, sanitary landfilling is a suitable technique as it imposes minimum adverse impacts on the environment. Strict guidelines are considered based on the environmental, community, and cost for site selection. Emphasis is on fully managing the landfill leachate and gas during operation. For these purposes, geomembrane layers are used to avoid leachate contamination, and gas monitoring/extraction wells are used for landfill gas management. Hence, this method is becoming the most popular landfill model for ultimate disposal sites in developed countries (Ahmed and Lan 2012). In contrast to gasification and anaerobic reactors, sanitary landfilling is a simple disposal procedure with low-cost and landscape restoring effects (Aziz et al. 2010). These factors influenced the popularity of sanitary landfills in many countries. However, landfills must be closely monitored during their design, operation, and post-closure due to the generation of landfill leachate and greenhouse gases (Ahmed and Lan 2012). Liner fractures may lead to groundwater contamination, and atmospheric contamination may occur from gas leaks due to breaks in the landfill cap of an engineered landfill.

11.1.3 Landfill Leachate

Landfill leachate is a water-based solution that has dissolved or entrained environmentally harmful substances that may enter the environment through degrad-

ing waste in the landfill. Many groundwater pollution incidents have been reported involving landfill leachate (Christensen et al. 2001). Therefore, leachate is considered as a hazardous liquid and strict regulations have been enacted by many environmental protection authorities around the world (Rafizul and Alamgir 2012). Landfill leachate is generated from rainwater that passes through the waste within the solid waste dumping facility. The moisture that already exists in the waste is also involved in the generation of leachate (El-Fadel et al. 2002).

Leachate consists of different organic and inorganic compounds that may be either dissolved or suspended and transported as a plume into the aquifer or away from the dumpsite following the land gradient. Landfill leachate plumes are not much wider than the landfill and not beyond 2,000 m from the landfill but show narrow plume movement (Christensen et al. 2001). The higher density ($\sim 1.014 \text{ g/cm}^{-3}$ at 10°C) caused by the high salt content of leachate may lead to an initial sinking of the leachate plume with groundwater while undergoing limited lateral or transverse mixing (Christensen et al. 2001). The viscosities of the leachate also differ from the groundwater, but very few data exist on leachate viscosity. The high electrical conductivity of landfill leachate is also a very important parameter to understand the leachate-contaminated subsurface environment, particularly for predicting leachate flow and transport through the subsurface. These subsurface data can be observed by employing advanced geophysical techniques mainly based on the conductive nature of the landfill leachate.

11.2 Leachate Formation Mechanisms

Landfill leachate is generated through a series of physical, chemical, and microbiological processes. The breakdown of larger waste materials into smaller fractions during the manual mixing of waste, while the liquids elute and percolate, is the main physical process. The oxidation/reduction processes during waste degradation are included in the chemical processes. For example, nitrate and ammonium ion oxidation to nitrogen gas is a dominant chemical process as leachate has considerable nitrate species. However, it is difficult to distinguish a single process in the landfill leachate since a combination of these processes is actively involved in generating the leachate. Landfill leachate is typically a strongly reduced matrix with a great capacity for donating electrons (e.g., donation of electrons via conversion of ammonium ions to nitrate). The electrons produced are accepted by dissolved or solid aquifer electron acceptors (e.g., nitrate, oxygen, sulfate, and ferric ions) (Christensen et al. 2001). Furthermore, organic matter dominates the reduction capacity, and ammonium and methane also contribute significantly (Christensen et al. 2001). A lysimeter-based study has shown a clear pattern between rainfall and the formation of landfill leachate (Rafizul and Alamgir 2012). The natural attenuation involved during transportation of landfill leachate is the main reason for changing its initial characteristics (Christensen et al. 2001; Mayakaduwa et al. 2012).

11.3 Types of Landfill Leachate

11.3.1 *Acetogenic Leachate*

The microbiological decomposition processes occurring within waste in a landfill play a crucial role determining leachate characteristics (Irene 1996). During the second phase, anaerobic and facultative organisms (acidogenic and acetogenic bacteria) hydrolyze and ferment cellulose and other putrescible materials. The resulting simpler soluble compounds such as volatile fatty acids and alcohols may cause high biochemical oxygen demand (BOD) in leachate which is called as “acetogenic leachate.” Acetogenic leachate is characterized by acidic pH, high BOD/chemical oxygen demand (COD) ratio, strong unpleasant smells, and high concentrations of ammonium nitrogen (Table 11.2) (Christensen et al. 2001). According to Harmsen (1983), >95 % of the dissolved organic carbon (DOC) in acetogenic leachate consists of volatile fatty acids and only 1.3 % accounts for high molecular weight compounds (MW > 1,000) (Harmsen 1983). Volatile amines and alcohols are also found in acetogenic leachate. Shuokr et al. (2010) reported that the volatile matter content in the acetogenic phase may be the reason for acidic pH in the leachate (Shuokr et al. 2010). In addition, this type of leachate may contain a considerable concentration of inorganic ions such as chloride, sulfate, calcium, and magnesium (Irene 1996).

11.3.2 *Methanogenic Leachate*

The acidic phase may last for several years and then slow-growing methanogenic bacteria start to establish gradually consuming simple organic compounds released during the second phase. The methanogenic leachate produced during this phase has an alkaline pH (Ehring 1988), lower BOD (Robinson 2007), and lower BOD/COD ratio and a consequent decrease in solubility of inorganics and heavy metals (Irene 1996). In this type of leachate, 32 % of DOC consists of high-molecular-weight compounds (MW > 1,000), such as humic and fulvic acids, which are not easily degradable. In addition, inorganic macrocomponents, such as sulfate, are lower during the methanogenic phase due to the microbial reduction of sulfate to sulfide (Christensen et al. 2001). Moreover, no volatile amines and alcohols can be found and ammonia is present in high concentration, which typically inhibits the biological degradation process (Harmsen 1983; Shuokr et al. 2010). Such stabilized leachate may persist for many decades or centuries. However, several inorganic macrocomponents (e.g., Cl, Na, and K) are not significantly different between acetogenic and methanogenic leachates (Christensen et al. 2001).

Table 11.2 Composition of the acetogenic and methanogenic landfill leachates in the Gohagoda landfill leachate

Parameter*	Values from the literature				Gohagoda leachate
	Acetogenic leachate		Methanogenic leachate		
	Al-Wabel; Christensen (Christensen et al. 2001; Al-Wabel et al. 2011)	Robinson (Robinson 2007)	Hunice; Christensen (Hunice et al. 2012)	Robinson (Robinson 2007)	
pH	5.9–6.3	5.5–7.0	7.9	7.5–8.5	8–8.6
Conductivity	6.3–42.5	7–30	37.2	<1	8.96–29.6
BOD	–	4,000–30,000	4,250	<500–1,000	21.6–3,590
COD	13,900–22,350	10,000–50,000	8,038	2,000–6,000	70–69,700
BOD/COD ratio	0.58 ^a		0.06 ^a		0.15
Alkalinity	–	2,000–10,000	13,200	10,000–30,000	725–39,606
Ammonium nitrogen	–	750–2,000	1,430	1,500–3,000	6–4,095
Nitrate-nitrogen	–	<1	–	<0.1	1–765
Phosphate	–	5–20	22.8	1,000–3,000	2–258
Sulphate	70–1,750 ^a		10–420 ^a		–
Chloride		1,000–2,000	7,000	2,000–4,000	68–723
Zinc	0.108–0.226	5–20	1.767	<0.01–0.05	0.2–1.15
Cadmium	<0.002	<0.1–<0.2	<0.005	<0.02–0.1	0.004–0.062
Nickel	0.384–0.718	<0.1–<1	0.597	<0.05–0.1	0.133–0.532
Chromium	0.21–0.336	1–<0.5	0.354	0.02–5	0.021–0.323
Copper	0.124–0.246	<0.1	0.145	<0.3–2	0.048–0.257
Lead	<0.04	<0.1–<0.5	<0.05	<0.05–0.2	0.015–0.416
Magnesium	50–1,150 ^a		40–350 ^a		20–166
Manganese	0.3–65 ^a		0.03–45 ^a		0.155–1.203
Iron	20–2,100 ^a		3–280 ^a		0.3–318

*All in mg/L except pH, BOD/COD ratio and EC (mS cm⁻¹), a) according to Christensen et al. (2001) and Abbas et al. (2009)

11.4 Toxicity of Landfill Leachate

Leachate has been identified by many countries as a toxic surface and groundwater and soil contaminant (Mor et al. 2006; Sun et al. 2001; Abbas et al. 2009). In addition, the landfill leachate liquid possesses a strong reducing ability under methanogenic conditions. Many studies are available on either direct experimental determinations of contaminants or estimates through mathematical modeling (Mor et al. 2006). Landfill leachate is highly toxic to higher plants, algae, invertebrates, fish, and humans (Langler 2004; Natale et al. 2008). Ammonium may be present in leachate at high concentrations for years and can cause considerable toxic effects to fish (Christensen et al. 2001). High toxicity was reported for algae, daphnids, and

bacteria in tests of samples collected close to a landfill with a decrease in toxicity identified with increasing distance from the landfill (Christensen et al. 2001).

Landfill leachate is a major source of natural organic matter (NOM) for water particularly in the developing world. The increase in organic compounds, particularly DOC, in the leachate is a source of trihalomethanes (THMs) (Weragoda 2005; Stuart et al. 2001). Most of these THMs have carcinogenic and mutagenic or possibly teratogenic properties (Weragoda 2005). In addition, some of these emerging contaminants may be identified as endocrine-disrupting chemicals (Ramakrishnan et al. 2013).

11.5 General Leachate Composition

The composition of landfill leachate can change due to rainfall or prevailing weather conditions during the waste degradation period, different management practices, waste characteristics, and depth of the MSW column. In addition, landfill design and operation procedures such as the degree of compaction, leachate recirculation steps, and internal landfill processes, such as anaerobic digestion steps, are major factors determining leachate composition (Rafizul and Alamgir 2012; Christensen et al. 2001; El-Fadel et al. 1997). Among these factors, moisture is a critical factor for waste degradation and, hence, for leachate composition (Rafizul and Alamgir 2012). However, no standard protocol for sampling, filtration, or storage of leachate samples exists for analysis (Christensen et al. 2001). For example, colloids have considerable affinity for complexation and this involves measuring the actual metal concentration. Many characterization studies have been based on only a few samples from each landfill as the cost and complexity of the experiments are very high. However, understanding leachate composition is very important for planning and determining remedial measures (Rafizul and Alamgir 2012). Hence, it is necessary to determine the actual pollution state such as the amount of contaminants and their generation and degradation rate in a particular region or country rather than copying the treatment methods from any region. Due to the complexity of landfill leachate, different ways are used to explain its composition based on many criteria. The composition of a landfill leachate can be explained by dividing it into four groups of organics (e.g., Dissolved Organic Matter as total organic carbon (TOC), DOC, and COD), inorganics (e.g., Ca, Mg, NH_4^+ , SO_4^{2+} , and Cl^-), heavy metals (e.g., Cd, Pb, Ni, and Zn), and xenobiotic organic compounds (XOC) (e.g., benzene, phenol, and trichloroethene).

11.5.1 DOM

DOM is a bulk parameter comprising a variety of organic degradation products ranging from small volatile acids to refractory fulvic- and humic-like compounds (Christensen et al. 2001). Therefore, TOC, DOC, non-volatile organic carbon

(NVOC), or COD is expressed as DOM. No study has given adequate attention to understanding the composition of DOM in landfill leachate and its fate in the environment. Only a very few studies have been published on DOM in landfill leachate. The DOC in leachate originates from the anaerobic decomposition of organic waste that causes numerous environmental effects, such as decreased removal of heavy metals and depleting dissolved oxygen in groundwater sources (Christensen et al. 1998). DOC remains as non-biodegradable compounds and may even be resistant to biological treatment (Zouboulis et al. 2004). Volatile fatty acids constitute a substantial fraction of DOC and show an easily degrading pattern in laboratory-based studies of the acetogenic leachate. But, similar studies on the methanogenic leachate have revealed the recalcitrant nature of DOM (Christensen et al. 2001). However, according to a study based on DOC and its fate, the DOC concentration in the leachate plume decreases with time (Christensen et al. 2001). Conversely, TOC well described the total amount of organic carbon in the leachate matrices. Leachate in active landfill sites contains higher TOC than that from closed landfill sites due to the high decomposition rate (Irene 1996). The ratio of COD to TOC indirectly reflects the organic matter characteristics of the leachate and the particular ratio can be used to determine the rough age of the landfill (Irene 1996).

11.5.2 BOD–COD

COD describes the organic matter content that is susceptible to oxidation by a strong chemical agent such as potassium dichromate. This parameter reflects the changes in solid waste degradability at dumpsites and the amount of organic contaminant (Irene 1996). Most of the leachates from the early stages (first year) of a landfill operation show high COD (>20,000 mg/L). With time, the landfill material ages and the COD stabilizes at $\leq 3,000$ mg/L (Irene 1996). BOD describes the organic matter content that is susceptible to oxidation by biological activities. High BOD occurs in acetogenic leachate with values of 4,000–30,000 mg/L, whereas methanogenic leachate carries lower values of 500–1,000 mg/L (Robinson 2007).

11.5.3 Solids

Determining the different fractions of solids in a landfill leachate is very important to understand the behavior of microbial degradation processes. For instance, it is interpreted that greater total suspended solid (TSS) concentrations reflect higher enzyme activity. The TSS concentration of leachate depends mostly on the abundance of microorganisms as well as the dilution conditions. Volatile-suspended solids (VSSs) could be directly proportional to microbial mass. In addition, VSS is frequently used as an estimate of the concentration of the active microorganisms in a biological treatment unit, but it is an imperfect measure of the active mass. VSS is also considered a useful design and management parameter for wastewater.

Volatile solids (VSs) are often interpreted as a measure of organic matter. This is not precisely true as the combustion of many pure organic compounds results in the formation of ash and many inorganic salts are volatilized during ignition. It includes losses due to decomposition or volatilization of some mineral salts.

11.5.4 Nutrients

Nitrate, phosphate, sulfate, and ammonium nitrogen concentrations are the principal nutrients of concern in leachate discharge and generally depend on the waste composition in landfills. Robinson and Luo (1991) observed the composition of leachate generated from very large landfills and reported typical concentrations of nitrate and phosphate of 2.5 and 27.6 mg/L, respectively (Robinson and Luo 1991). Bagchi (1990) reported that the overall nitrate concentration range in leachate is up to 250 mg/L (Bagchi 1990). Ranges of 5–10 and 20–40 mg/L total phosphorous and ammonium nitrogen, respectively, are observed in leachates from mature landfills (Shuokr et al. 2010). Sulfate is high in concentration in the landfill leachate, but low concentrations can be found in an active methanogenic leachate because the sulfate reduces to S^{2-} ions (Christensen et al. 2001). Decomposition of waste or ash is the main source of released sulfate. The disposal of plaster board made of gypsum ($CaSO_4 \cdot 2H_2O$) also releases sulfate into the leachate. Discharge of untreated leachate with high nutrient concentrations may accelerate eutrophication of lakes and reservoirs and may lead to other adverse effects such as the depletion of dissolved oxygen in receiving water, the toxicity to aquatic life, and an adverse impact on public health.

11.5.5 Heavy Metals

Heavy metals in landfill leachate are controversial. Many researchers have reported fairly low concentrations of heavy metals and their strong attenuation through precipitation and sorption (e.g., processes such as adsorption, absorption, surface complexation, surface precipitation, and ion exchange) in landfill leachate, suggesting a low risk to the environment (Christensen et al. 2001). Nevertheless, some researchers have reported opposite observations. For example, high concentrations of Cd, Hg, Ni, Mn, Cu, Zn, and Pb have been reported in leachate and these metals show enhanced transportation with DOC derivatives mainly by the anaerobic degradation of organic compounds, such as humic, fulvic, and hydrophilic acids, present in the leachate (Robinson 2007; Asadi 2008; Christensen et al. 1996). In addition, DOC contributes to the leachate color, turning it dark brown due to the complexation of ferric hydroxide colloids with humic and fulvic substances (Chu et al. 1994). Some heavy metals in reduced states (e.g., chromium iron as Cr^{3+}) have been reported in methanogenic leachate.

11.5.6 XOC

Very broad ranges of XOCs have been reported in landfill leachate and most are aromatic hydrocarbons (Christensen et al. 2001). These XOCs are organic chemicals identified as unknown and individual pollutants in the leachate and are reported to cause serious biological effects. Phenols, halogenated hydrocarbons, chlorinated aliphatics Perchloroethylene and Trichloroethene (PCE and TCE), and aromatic hydrocarbons (Mor et al. 2006; Asadi 2008) are included in the group of XOCs common in leachate. In addition, organic waste water contaminants, such as cholesterol, N, N-diethyltoluamide (an insect repellent), and tri(2-chloroethyl) phosphate (a fire retardant), were found in the landfill leachate-affected groundwater samples (Barnes et al. 2004). Newly identified XOCs, such as herbicide Mecoprop or Methylchlorophenoxypropionic acid (MCP), have frequently been observed in leachate but little attention is given yet to understanding their degradation in the anaerobic environment (Christensen et al. 2001). However, analyzing XOCs is a complicated procedure as poor sampling protocols, high labor, and sampling costs hamper analysis. Aromatic hydrocarbons readily degrade in aerobic environments but a slower degradation rate has been detected in reducing environments (e.g., benzene). Nevertheless, degradation of XOCs and their associated products are still lacking a precise understanding.

11.5.7 Microbial Communities

Although the microorganisms involved in landfill leachate have not been studied in detail, bacteria and their activities in leachate have been investigated in a few studies. Methanogens, sulfate reducers, iron reducers, manganese reducers, and denitrifiers have been identified commonly in leachate plumes. Diverse microbial communities have been identified in leachate plumes and are believed to be responsible for the redox processes (Christensen et al. 2001). Some bacterial species, such as eubacteria and archaea, dominate landfill leachate-contaminated groundwater (Christensen et al. 2001; Ludvigsen et al. 1999). The microbial population closest to the landfill appear to be the most active in response to the pollutants. In addition, the methanogens and sulfate-reducing bacteria are abundant close to the landfill. However, the number of microorganisms decrease with plume length (Ludvigsen et al. 1999).

11.6 Case Study: Gohagoda Landfill Leachate

Many characterization studies and extensive reviews of the composition of landfill leachates are available for developed nations, particularly temperate countries, but only a few studies have reported on the transport and fate of landfill leachate in the

tropics, particularly in the developing Asian region (Kale et al. 2010; Mor et al. 2006; Vasanthi et al. 2008). A detailed characterization of the landfill is a main limitation for designing a treatment plant (Tatsi and Zouboulis 2002). The situation of leachates from Sri Lankan dumpsites is typical of Asian countries, and no detailed characterization data are available. However, a few studies have been carried out to characterize leachates generated from the Gohagoda dumpsite in Sri Lanka. A groundwater quality study based on the shallow wells and drains around the Gohagoda dumpsite revealed high contamination in the Mahaweli River with BOD, COD, nitrate, and phosphate values of 20,000, 48,000, 64, and 56 mg/L, respectively (Wimalasuriya et al. 2011). But none of these studies focused on a long-term characterization of the leachate focusing on the interaction between temporal and spatial variation and flow and transport of leachate through subsurface. The following is a case study of such a characterization.

11.6.1 Gohagoda Open Dumpsite

The Gohagoda open dumpsite is situated adjacent to the northwestern boundary of Kandy city, Sri Lanka. It has been used for dumping waste from the world heritage city, Kandy since the 1960s. In 2003, the dumpsite was semi-engineered by extending the landfill area to 25,000 m² and including provisions for leachate treatment. However, the design period was only 2–3 years old and, currently, open dumping is taking place and the leachate treatment process is not functioning. About 130 t MSW/day including waste from slaughter houses, fish markets, households, and non-infectious hospital waste are being dumped without any sorting or pretreatment (Welikannage and Liyanage 2009).

11.6.2 Parameters

The landfill leachate used in the experiment was collected from the Gohagoda open dumpsite from June 2011 to October 2012. The leachate samples were collected at four sampling points of the drainage canal with recommended procedures as summarized in Table 11.3. Figure 11.3 shows the sampling points; GS1 and GS4 were located at the start and end points of the canal, whereas GS2 and GS3 were in the middle. The collected leachate samples were characterized for pH, temperature, conductivity, alkalinity, and total dissolved solids (TDS) under field conditions and then immediately transferred to the laboratory at 4 °C for other experiments such as nutrient content, COD, Cl⁻, solids, TOC, DOC, and a metal analysis (Table 11.3). A resistivity survey was also performed using ABEM Terameter 300-c SAS, Sweden (one-dimensional (1D) resistivity survey) and AGI (Advanced Geosciences Inc, Austin, TX, USA) Mini-sting system with accessories (2D imaging). Resistivity data were collected by three 1D survey lines and two 2D profile lines covering the point where the leachate collected at the river (Fig. 11.3). The 1D data processing

Table 11.3 Summary of the analytical methods to determine the major chemical constituents in Gohagoda open landfill leachate, Kandy

Constituents	Method/reference
pH	ROSS sure-flow combination epoxy body electrode
EC	Conductivity meter (Orion 5 star series)
BOD ₅	Winkler method (American public health association 2005)
COD	Spectrophotometer (HACH DRB 200)
TOC	TOC analyzer (Analytikjena Multi N/C 2100)
Alkalinity	Titrimetric method (American public health association 2005)
Ammonia-nitrogen	Iron selective electrode
Nitrate-nitrogen	Cadmium reduction method
Nitrite-nitrogen	Diazotization method
Phosphate	Ascorbic acid method
Chloride	Iron selective electrode
Zinc	Atomic adsorption spectrophotometer (AAS) (GBC 933 Australia)
Cadmium	
Nickel	
Chromium	
Copper	
Lead	
Iron	
Manganese	

*All in mg/L except pH and electrical conductivity (EC) (mS cm⁻¹)

BOD, Biochemical oxygen demand; COD, chemical oxygen demand; TOC, total organic carbon



Fig. 11.3 Schematic diagram of the leachate drainage channel (red arrows), leachate sampling points (yellow dots), resistivity survey area (yellow rectangle), and 2D profile lines 4 and 5 with direction X-Y (black dotted line) at the Gohagoda dump site

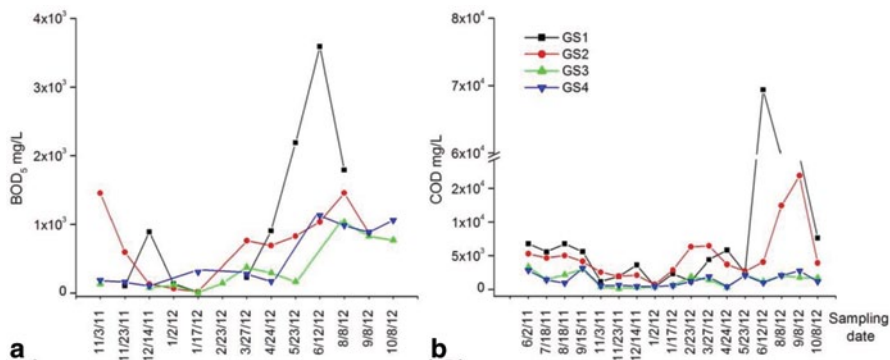


Fig. 11.4 (a) pH and (b) alkalinity variations in the leachate samples analyzed

was carried out using the Resist freeware package while maintaining the root mean square error < 5 %. The 2D data were processed via Earth Imager licensed software by fixing resistivity at 10–400 Ωm.

11.6.3 Leachate Characteristics

11.6.3.1 pH and Conductivity

Figure 11.4a shows the pH variation during the study period. The pH was 8–8.6 during all samplings with a few exceptions. The pH changed acidic during the later study period. This may be due to the uncontrolled open dumping of MSW with manual mixing of waste and enhancing microbial activity due to the influence of rainfall (Trankler et al. 2005). Degradation of fresh waste can also decrease pH. The alkaline pH was due to mineralization of carbonates, bicarbonates, and hydroxides in the well-established methanogenic phase of the landfill (Robinson 2007; Maqbool et al. 2011). Hence, a phase change from acetogenic to methanogenic can be effectively identified by pH changes in the landfill leachate (Trankler et al. 2005). In addition, the recorded electrical conductivity (EC) of the leachate samples was high at 3.2–31.4 mS/cm, indicating a high content of dissolved salts. However, due to dilution and flushing of organic and inorganic materials, the EC values decreased towards the riverside.

11.6.3.2 Alkalinity and Hardness

The alkalinity in the Gohagoda leachate was 725–39,606 mg/L (Fig. 11.4b). Because the alkalinity is a measure of the acid neutralizing capacity and, hence, is a function of HCO₃⁻ and CO₃²⁻ content (William 1997), the dissolution of metal carbonates un-

der prevailing pH conditions may have been the reason for the increase in alkalinity with time (Bhambulkar 2011). Hardness is normally expressed as the total concentration of Mg^{2+} and Ca^{2+} in mg/L and it was 15–800 mg/L during the study period. GS2 showed the highest hardness value at the beginning but it decreased rapidly thereafter. The pattern of variation was narrow except GS4. Thus, it was evident that GS1 and GS2 were highly contaminated with Mg^{2+} and Ca^{2+} multivalent cations, which may be due to soaps, detergents, batteries, and other types of industrial and household waste. The reason for the hardness decreasing with time could be infiltration and attenuation by soil. Under alkaline pH conditions, adsorption or precipitation mechanisms attenuate Mg^{2+} and Ca^{2+} ions in leachate in surrounding soils that are rich in clay minerals. In addition, chloride was 68–723 mg/L during the study period (Table 11.2). Farm animal waste, household waste, and septic effluent might be sources for the high chloride levels in leachate (Mor et al. 2006).

11.6.3.3 BOD and COD

Figure 11.5a and b illustrates the BOD_5 and COD variation throughout the leachate characterization period at the Gohagoda landfill site. The maximum BOD_5 was 3,590 mg/L at the closest point to the dumpsite. However, the BOD_5 was <2,190 mg/L at all other sampling times, indicating typical methanogenic phase conditions (Robinson 2007). Furthermore, low BOD_5 values with continuously fluctuating patterns were observed during the study period. At the beginning of the characterization, very significantly high BOD_5 values of 27,500 mg/L were recorded at the closest point to the landfill (GS1 point), indicating typical acetogenic phase leachate characteristics (Wijesekara et al. 2010). COD stabilized at $\leq 3,000$ mg/L with time at the Gohagoda site. These values are consistent with other studies for typical methanogenic landfill leachate (Irene 1996). A highly concentrated landfill leachate can be generated in biodegradable waste rich landfill cells during the initial period of refuse degradation (Tatsi and Zouboulis 2002; Trankler et al. 2005). As typical South Asian MSW landfills, a composition study at the Gohagoda dumpsite for solid waste revealed that there was a high amount of biodegradable waste, which has a direct relationship with the high organic content of leachate (Trankler et al. 2005; Menikpura and Basnayake 2009).

11.6.3.4 TOC/DOC

Average TOC and DOC values were 36,955 and 28,493 mg/L, respectively, during the dry season, and a low COD/TOC ratio (1.59) was observed in the Gohagoda leachate. These results indirectly indicate the age of the Gohagoda landfill site as >20 years and the presence of a more oxidized state of organic carbon for a less readily available energy source for the growth of microorganisms (Irene 1996).

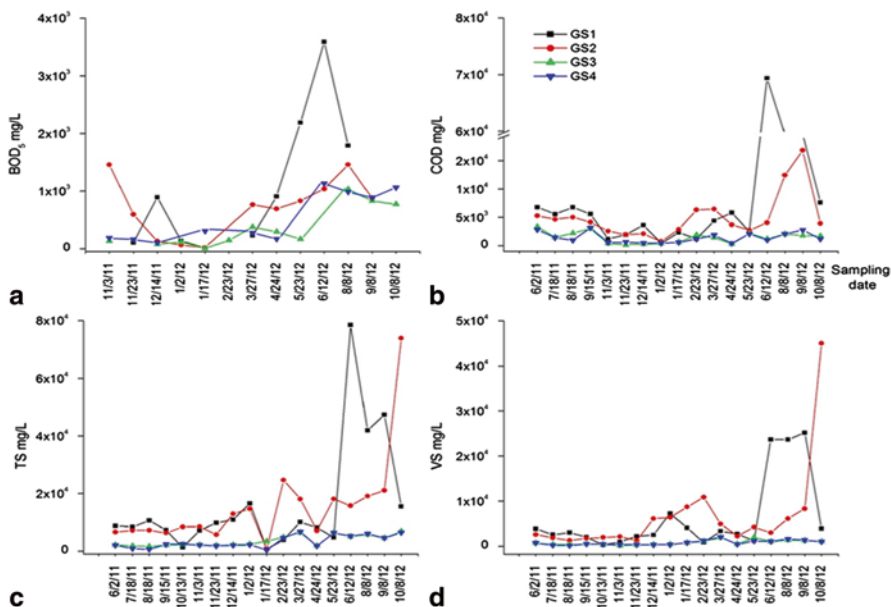


Fig. 11.5 Variation in the concentrations of **a** BOD₅, **b** COD, **c** TSS, and **d** VS in the leachate samples analyzed

11.6.3.5 Solids

Figure 11.5c and d reflects the Total Solids (TS) and Volatile Solids (VS) variations during the study period at the Gohagoda landfill. The TS and VS values were <20,000 and 10,000 mg/L, respectively, which agreed with the previous literature values for methanogenic phase leachate (Chu et al. 1994). However, on a few occasions very high TS and VS concentrations of 80,000 and 45,000 mg/L, respectively, were observed. The spatial variations in TS and VS had many similarities. The average Total Suspended Solids (TSS) and Volatile Suspended Solids (VSS) concentrations during the study period were 1,493 and 416 mg/L, respectively. The mean VSS values of the leachate at various landfills are 50–200 mg/L, which is close to the observed values (10–4,810 mg/L) (Fan et al. 2006). The VSS value of an old landfill (>10 years) is 7 mg/L (Kang et al. 2002). In addition, the concentration of all analyzed solid parameters decreased from the dumpsite to riverside, and this may have been due to the coagulation and settling of solid particles in the adjoining paddy field soils. Overall, the solid parameters analyzed indicate that the Gohagoda leachate is in the methanogenic stage.

11.6.3.6 Nutrients

Among the nutrients, nitrogenous compounds were observed in high concentrations. Figure 11.6a shows the nitrate-N variation in the leachate samples analyzed.

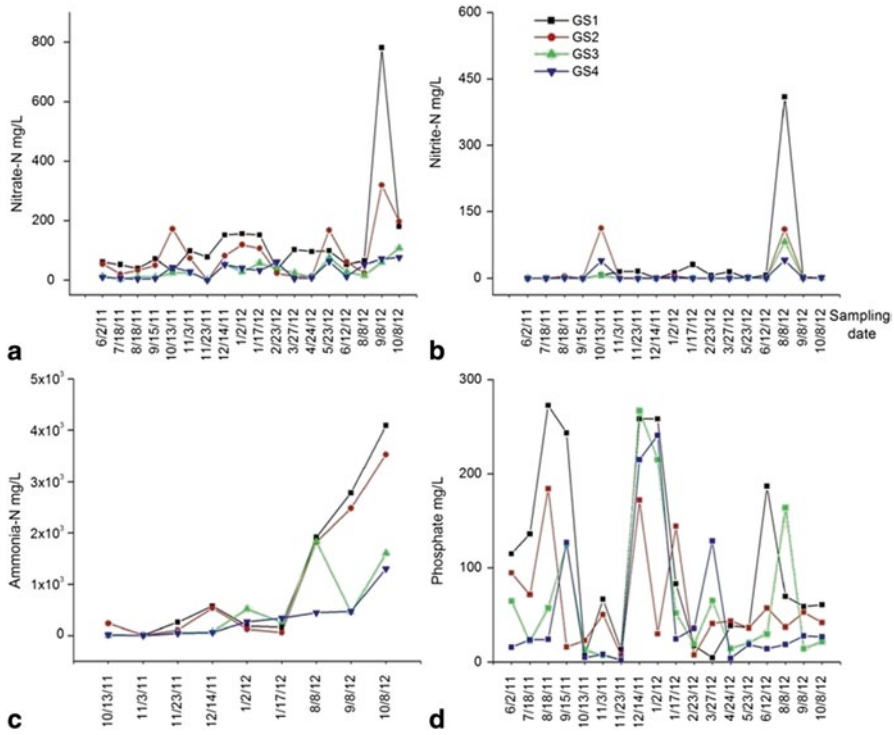


Fig. 11.6 Variations in the concentrations of **a** nitrate-N, **b** nitrite-N, **c** ammonia-N, and **d** phosphate in the leachate samples analyzed

Nitrate-N ranged from 1 to 765 mg/L. Sewage, fertilizer, farm animal waste, and food waste are sources of nitrate in leachate. Higher concentrations of nitrate-N resulting during the final period may have been due to rainwater ingress into the landfill that promoted solubilization of pollutants from actively decomposing waste mass into the leachate. Furthermore, nitrite-N was 0.1–410 mg/L, indicating a complex fluctuation pattern (Fig. 11.6b). A high concentration of nitrite-N is observed in methanogenic leachate worldwide (Robinson 2007). Ammonium-N may be present in leachate due to the fermentable organic matter and the high protein concentration (Mor et al. 2006). Ammonium-N is a major reducing agent in the leachate and, thus, is involved in increasing nitrate concentration. The ammonia-N results in the Gohagoda leachate fluctuated widely at 6–4,095 mg/L (Fig. 11.6c). Considerably high concentrations (3,000 mg/L) were observed at the end of the study with heavy rainfall. Because ammonia is a product of anaerobic protein metabolism, stabilizing anaerobic digestion may have led to the accumulation of ammonia during the final time period. Phosphate levels varied considerably within wide ranges exceeding the country’s standard values for wastewater discharge to inland waters at 2 mg/L (Fig. 11.6d). All nutrients generally showed a sudden increase in concentrations immediately after the heavy rainfall. This was probably due to enhanced leaching of

nutrients from the fresh waste dumped at the site during the study period followed by the dilution effects of rain (El-Fadel et al. 1997).

11.6.3.7 Chloride

Chloride in leachate is a major non-reactive or inert component and, thus, chloride does not undergo any chemical or physicochemical reactions in the leachate plume. Therefore, dilution is the main attenuation mechanism for chloride (Christensen et al. 2001). However, chloride can contribute to the formation of toxic dioxin gas. The chloride concentration during the study period was 68–723 mg/L. Farm animal waste, household waste, and septic effluents could be the high chloride sources in the leachate (Mor et al. 2006). High rainfall during the last sampling period may have caused accelerated run-off from the dumpsite, resulting, insignificantly, increased chloride levels. However, chloride ions are found in the deepest parts of leachate plumes that affect aquifers; thus, it is an important parameter to model.

11.6.3.8 Heavy Metals

The presence of high levels of heavy metals in the Gohagoda leachate suggests their origin could be from various wastes dumped in the landfill (Fig. 11.7). The presence of alloys, paints, lamp filaments, electrical wiring batteries, ceramics, and automotive parts in a dumpsite can be reasons for heavy metal contaminations (Trabelsi et al. 2009; Fetter 1993). A high concentration of Fe in the leachate may be from Fe scraps and Fe-containing carbonates dumped on the landfill. The presence of Pb exceeding the country's wastewater discharge permissible level of 0.1 mg/L may be attributed to the disposal of batteries, lead-based paints, chemicals for photo-processing, and lead pipe (Mor et al. 2006). High concentrations of Zn suggest the presence of fluorescent tubes, batteries, and a variety of food wastes. Possible sources of cadmium may be dry cell batteries and paint (Aderemi et al. 2011). Aeration by mechanical mixing of waste accelerates the release of heavy metals into the leachate, which contaminates open water bodies such as rivers as well as ground-water resources through percolation (Mor et al. 2006). In contrast, the alkaline pH enhanced precipitation of cations; thus, lower concentrations are reported in methanogenic phase leachate (Christensen et al. 2001). The sulfide-producing conditions also influence the low concentrations of metal ions.

11.6.3.9 Resistivity Survey

The resistivity data revealed that the main outflow pathway of landfill leachate to the nearby Mahaweli River is characterized as a plunging basin towards the river, and its flow is confined to the near surface (Fig. 11.8). The flow pattern may have been influenced by river water inflow at <3 m level, which would prevent delineating possible perch water pockets (Wijsekara et al. 2013).

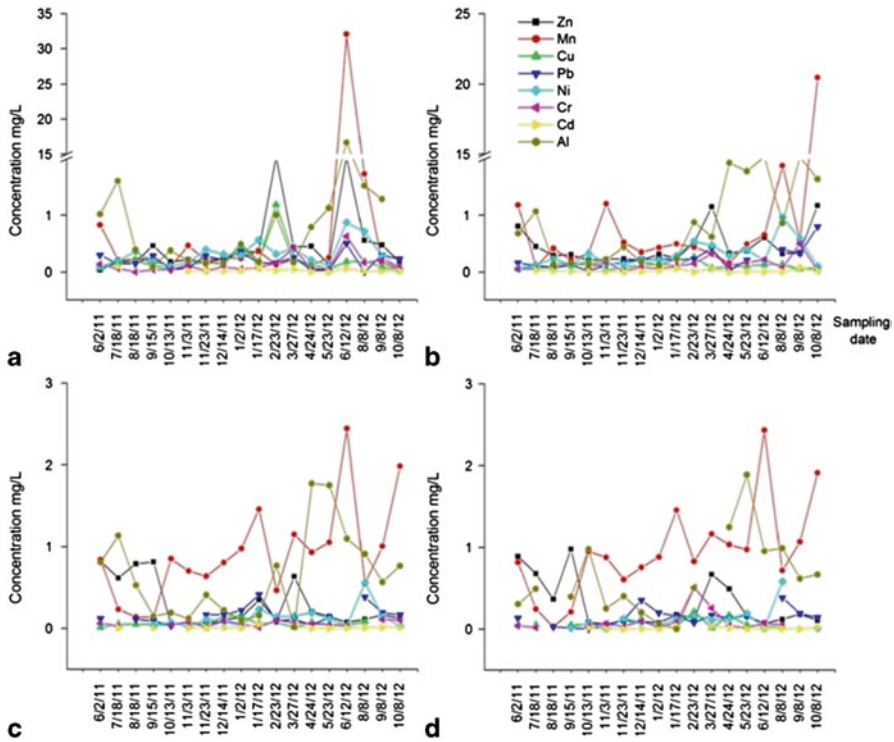


Fig. 11.7 Variations in the heavy metal concentrations at the a GS1, b GS2, c GS3, and d GS4 sampling locations

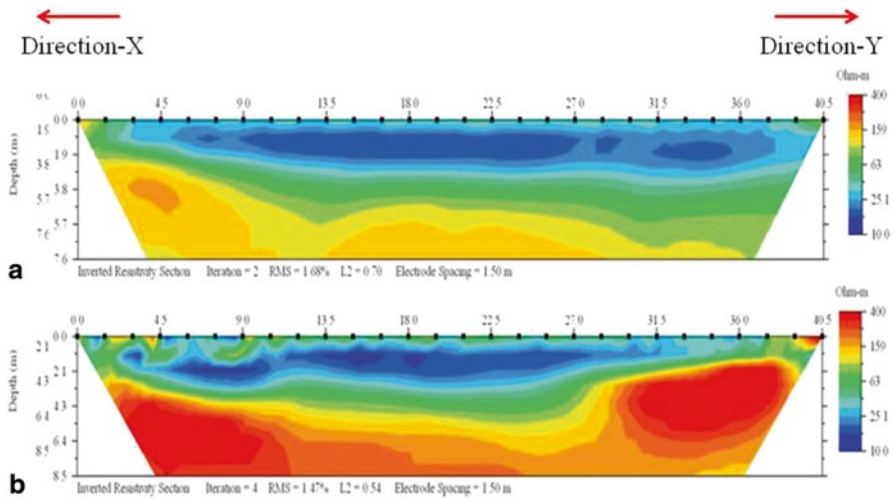


Fig. 11.8 Images of 2D profiles (a) line-4 and (b) line-5 indicate that the leachate flow is very shallow and limited to the 3-m level. Blue color indicates possible leachate plume with low resistivity values in the Y direction

11.7 Leachate Treatment Technologies

An important part of maintaining a landfill is managing the leachate through proper treatment methods designed to prevent pollution of surrounding ground and surface water. Leachate treatment technologies fall into two basic types of biological and physical/chemical treatments. Integrated systems that combine the two are often used for larger systems depending on treatment goals. The most common biological treatment is activated sludge, which is a suspended-growth process that uses aerobic microorganisms to biodegrade organic contaminants in the leachate. The leachate is aerated in an open tank with diffusers or mechanical aerators. Constructed wetlands are also used for biological treatment (Sundaravadivel and Vigneswaran 2001). However, treating old landfill leachate is a very difficult task using conventional biological treatment processes (Ahmed and Lan 2012). Air or ammonia-stripping, adsorption, and membrane filtration are major physical leachate treatment methods, whereas coagulation–flocculation, chemical precipitation, and chemical and electrochemical oxidation methods are the common chemical methods used for landfill leachate treatment (Ahmed and Lan 2012; Amokrane et al. 1997; Ahn et al. 2002; Chiang et al. 2001; Lin and Chang 2000; Steensen 1997; Marttinen et al. 2002; Cossu et al. 1998). The membrane bioreactor (MBR) (Ahmed and Lan 2012; Amokrane et al. 1997; Cossu et al. 1998; Ahn et al. 2002; Chiang et al. 2001; Lin and Chiang 2000) technique is a promising alternative physical treatment method, as the membrane separation capacity of a MBR allows most microbial cells through the reactor resulting in an efficient biological digestion system (Ahmed and Lan 2012). Li et al. (1999) reported that ammonium removal can be achieved by chemical precipitation. In addition, a 66% COD and 50% ammonia removal were obtained by nanofiltration (Marttinen et al. 2002). Evaporation and reverse osmosis have been used to treat industrial landfill leachate (Di Palma et al. 2002). Further, combined processes successfully applied together include coagulation–flocculation + biological treatment; (Kargi and Pamukoglu 2003) photochemical oxidation + activated sludge; Fe(III) chloride coagulation + photo-oxidation; and ozonation + adsorption (Koh et al. 2004; Wang et al. 2002; Rivas et al. 2003). Several researchers have investigated efficiency of ozonation for treating landfill leachate (Steensen 1997; Baig et al. 1999; Silva et al. 2004). Activated carbon adsorption systems have also been used to treat landfill leachate and remove dissolved organics; however, most of these techniques are generally considered expensive treatment options and must often be combined with other treatment technologies to achieve the desired results. A few studies have demonstrated the use of nano-zero-valent iron (NZVI) as a leachate treatment, but this method is restricted to developed and temperate countries (Jun et al. 2009). However, landfill leachate treatment is a serious issue with no single suitable solution due to the complexity and variation in composition and many local and regional differences.

11.8 Summary

Landfill leachate is composed of a wide range of contaminants: dissolved organic matter, heavy metals, and xenobiotic organic compounds. Exposure of leachate to the soil and groundwater creates significant changes in the environment. Leachate can be categorized into two phases of acetogenic and methanogenic leachates. The dissolved organic matter in the leachate is a bulk parameter comprising a variety of organic degradation products ranging from small volatile acids to refractory fulvic- and humic-like compounds which remain as non-biodegradable compounds for years. The BOD in acetogenic leachate is high indicating presence of readily oxidizable matter for aerobic microorganisms, whereas methanogenic leachate has low BOD values. Most leachate from the early stages (first year) of landfill operation showed a high COD, but as the landfill material aged the COD stabilized at $\leq 3,000$ mg/L. Determining solid content is very important to understand the microbial degradation patterns, their abundance (e.g., active microbial mass), and enzyme activities. Nitrate, phosphate, sulfate, and ammonium nitrogen concentrations are the principal nutrients of concern in leachate discharge and generally depend on the waste composition in the landfills and the leachate phase. Among the nutrients, nitrogenous compounds were observed at high concentrations. Sewage, fertilizer, farm animal waste, and food waste may be the sources of nitrates in leachate. The presence of alloys, paints, lamp filaments, electrical wiring, batteries, ceramics, and automotive parts in a dumpsite are the reasons for high heavy metal concentrations in the leachate; hence, high concentrations of Cd, Hg, Ni, Mn, Cu, Zn, and Pb have been reported associated with leachate. Very board ranges of xenobiotic organic compounds have been reported in landfill leachate and most are aromatic hydrocarbons and XOCs, which cause serious biological effects. Phenols, halogenated hydrocarbons, chlorinated aliphatics (e.g., PCE and TCE), and aromatic hydrocarbons are the main XOCs found in leachate. An important part of maintaining a landfill is managing the leachate through proper treatment methods designed to prevent pollution of surrounding ground and surface waters. Hence, two basic categories of leachate treatment methods are biological and physical/chemical technologies used worldwide. The most common biological treatment is activated sludge, which is a suspended-growth process that uses aerobic microorganisms to biodegrade organic contaminants in leachate. Air or ammonia-stripping, adsorption, and membrane filtration are major physical leachate treatment methods, whereas coagulation–flocculation, chemical precipitation, chemical and electrochemical oxidation methods are the most common chemical methods used for landfill leachate treatment. However, no universal leachate treatment methods have been developed due to the complexity of leachate.

Acknowledgment This study was partly supported by the Korea Ministry of Environment as the Geo Advanced Innovative Action Project (G112-00056-0004-0).

References

- Abbas AA, Jingsong G, Ping LZ, Ya PY, Al-Rekabi WS (2009) Review on landfill leachate treatments. *J App Sci Res* 5(5):534–545
- Aderemi AO, Oriaku AV, Adewumi GA, Otitoloju AA (2011) Assessment of groundwater contamination by leachate near a municipal solid waste landfill. *Afr J Environ Sci Tech* 5(11):933–940
- Ahmed FN, Lan CQ (2012) Treatment of landfill leachate using membrane bioreactors: a review. *Desalination* 287:41–54
- Ahn DH, Yun-Chul C, Won-Seok C (2002) Use of coagulation and zeolite to enhance the biological treatment efficiency of high ammonia leachate. *J Environ Sci Health* 37(2):163–173
- Al-Wabel MI, Al Yehya WS, AL-Farraj AS, El-Maghraby SE (2011) Characteristics of landfill leachates and bio-solids of municipal solid waste (MSW) in Riyadh City, Saudi Arabia. *J Saudi Society Agri Sci* 10:65–70
- American public health association, (2005) Standard methods for the examination of water and wastewater, 21st edition New York
- Amokrane A, Comel C, Veron J (1997) Landfill leachate pretreatment by coagulation-flocculation. *War Res* 31(11):2775–2782
- Asadi M (2008) Investigation of heavy metals concentration in landfill leachate and reduction by different coagulants. The 7th International Conference on Environmental Engineering. Faculty of Environmental Engineering, Vilnius Gediminas Technical University, pp 484–488
- Aziz SQ, Aziz HA, Yusoff MS, Bashir MJK, Umar M (2010) Leachate characterization in semi-aerobic and anaerobic sanitary landfills: a comparative study. *J Environ Manage* 91(12):2608–2614
- Bagchi A (1990) Design, construction, and monitoring of sanitary landfill. 1st ed. Wiley, New Jersey
- Baig S, Coulomb I, Courant P, Liechi P (1999) Treatment of landfill leachates: lapeyrouse and satrod case studies. *Ozone Sci Eng* 21(1):1–22
- Barnes KK, Christenson SC, Kolpin DW, Focazio MJ, Furlong ET, Zaugg SD, Meyer MT, Barber LB (2004) Pharmaceuticals and other organic waste water contaminants within a leachate plume downgradient of a municipal landfill. *Ground Water Monit R* 24(2):119–126
- Bhambulkar AV (2011) Effects of Leachate Recirculation on a Landfill. *Int J Adv Eng Sci Tech* 11(2):286–291
- Chiang L, Chang J, Chung C (2001) Electrochemical oxidation combined with physical-chemical pretreatment processes for the treatment of refractory landfill leachate. *Environ Eng Sci* 18(6):369–378
- Christensen JB, Jensen DL, Christensen TH (1996) Effect of dissolved organic carbon on the mobility of cadmium, nickel and zinc in leachate polluted groundwater. *War Res* 30(12):3037–3049
- Christensen JB, Jensen DL, Gron C, Filip Z, Christensen TH (1998) Characterization of the dissolved organic carbon in landfill leachate-polluted groundwater. *War Res* 32(1):125–135
- Christensen TH, Kjeldsen P, Bjerg PL, Jensen DL, Christensen JB, Baun A, Albrechtsen HJ, Heron G (2001) Biogeochemistry of landfill leachate plumes. *App Geochem* 16(7–8):659–718
- Chu LM, Cheung KO, Wong MH (1994) Variation in the chemical properties of landfill leachate. *Environ Manage* 18(1):105–117
- Cossu R, Polcaro AM, Lavagnolo MC, Mascia M, Palmas S, Renoldi F (1998) electrochemical treatment of landfill leachate: oxidation at Ti/PbO₂ and Ti/SnO₂ anodes. *Environ Sci Tech* 32(22):3570–3573
- Di Palma L, Ferrantelli P, Merli C, Petrucci E (2002) Treatment of industrial landfill leachate by means of evaporation and reverse osmosis. *Waste Manage* 22(8):951–955
- Ehring HJ (1988) Water and element balances of landfills. *Int J Landfills* 20(103–116)
- El-Fadel M, Findikakis AN, Leckie JO (1997) Environmental impacts of solid waste landfilling. *J Environ Manage* 50(1):1–25

- El-Fadel M, Bou-Zeid E, Chahine W, Alayli B (2002) Temporal variation of leachate quality from pre-sorted and baled municipal solid waste with high organic and moisture content. *Waste Manage* 22(3):269–282
- Fan HJ, Shu HY, Yang HS, Chen WC (2006) Characteristics of landfill leachates in central Taiwan. *Sci Total Environ* 361(1–3):25–37
- Fetter CWWP (1993) *Contaminant hydrogeology*. 2nd ed. Waveland Press, Inc
- Harmsen J (1983) Identification of organic compounds in leachate from a waste tip. *War Res* 17:699–705
- Hartz KE, Ham RK (1983) Moisture level and movement effects on methane generation from landfill samples. *Waste Manage Res* 1:139–145
- Hunce SY, Akgul D, Demir G, Mertoglu B (2012) Solidification/stabilization of landfill leachate concentrate using different aggregate materials. *Waste Manage* 32(7):1394–1400
- Irene M (1996) Characteristics and treatment of leachates from domestic landfills. *Environ Int* 22(4):433–442
- Joseph K, Nagendran R, Palanivelu K (2002) Open dumps to sustainable landfills. CES ENVISION, monthly news letter of the ENVIS node under EMCBTA project at CES (AU/CES/NL-02) supported by Ministry of Environment and Forests, Government of India, Vol 1, No. 2
- Joseph K, Esakku S, Nagendran R, Visvanathan C (2005) A decision making tool for dumpsite rehabilitation in developing countries. *Proceedings Sardinia, International Waste Management and Landfill Symposium, Italy*
- Jun D, Yongsheng Z, Weihong Z, Mei H (2009) Laboratory study on sequenced permeable reactive barrier remediation for landfill leachate-contaminated groundwater. *J Hazard Mater* 161:224–230
- Kale SS, Kadam A, Kumar S, Pawar NJ (2010) Evaluating pollution potential of leachate from landfill site, from the Pune metropolitan city and its impact on shallow basaltic aquifers. *Environ Monitor Assess* 162:327–346
- Kang K-H, Shin HS, Park H (2002) Characterization of humic substances present in landfill leachates with different landfill ages and its implications. *War Res* 36(16):4023–4032
- Kargi F, Pamukoglu MY (2003) Powdered activated carbon added biological treatment of pre-treated landfill leachate in a fed-batch reactor. *Biotech Letters* 25(9):695–699
- Kılıç MY, Kestioglu K, Yonar T (2007) Landfill leachate treatment by the combination of physico-chemical methods with adsorption process. *J Biol Environ Sci* 1(1):37–43
- Koh I, Chen-Hamacher X, Hicke K, Thiemann W (2004) Leachate treatment by the combination of photochemical oxidation with biological process. *J Photochem Photobio Chem* 162:261–271
- Kuo WS (1999) Destruction of toxic organics in water by an injection-type downflow UV/O₃ oxidation reactor. *Ozone Sci Eng* 21(5):539–550
- Langler GJ (2004) *Aquatic toxicity and environmental impact of landfill leachate*. University of Brighton, p 3–6
- Li XZ, Zhao QL, Hao XD (1999) Ammonium removal from landfill leachate by chemical precipitation. *Waste Manag* 19:409–415
- Lin SH, Chang CH (2000) Treatment of landfill leachate by combined electro-fenton oxidation and sequencing batch reactor method. *Water Res* 34(17):4243–4249
- Loehr (1984) *Agricultural waste management: problems: processes and approaches*. New York, Cornell University, Department of Agricultural Engineering
- Ludvigsen L, Albrechtsen HJ, Ringelberg DB, Ekelund F, Christensen TH (1999) Distribution and composition of microbial populations in a landfill leachate contaminated aquifer (Grindsted, Denmark). *Microb Ecol* 37(3):197–207
- Maqbool F, Bhatti ZA, Malik AH, Pervez A, Mahmood Q (2011) Effect of landfill leachate on the stream water quality. *Int J Environ Res* 5(2):491–500
- Marttinen SK, Kettunen RH, Somunen KM, Soimasuo RM, Rintala JA (2002) Screening of physico-chemical methods for removal of organic material, nitrogen and toxicity from low strength landfill leachates. *Chemosphere* 46:851–858

- Mayakaduwa SS, Siriwardana AR, Wijesekara SSRMDHR, Basnayake BFA, Vithanage M (2012) Characterization of landfill leachate draining from Gohagoda municipal solid waste open dump site for dissolved organic carbon, nutrients and heavy metals. The 7th Asian Pacific Landfill Symposium. Indonesia
- Menikpura SNM, Basnayake BFA (2009) New applications of “Hess Law” and comparisons with models for determining calorific values of municipal solid wastes in the Sri Lankan context. *Renewable Energy* 34(6):1587–1594
- Mor S, Ravindra K, Dahiya RP, Chandra A (2006) Leachate characterization and assessment of groundwater pollution near municipal solid waste landfill site. *Environ Monitor Assess* 118:435–456
- Natale FD, Natale MD, Greco R, Lancia A, Laudante C, Musmarra D (2008) Groundwater protection from cadmium contamination by permeable reactive barriers. *J Hazard Mater* 160:428–434
- National Environmental (Protection and Quality) Regulations. No. 47 of 1980., No.1 of 2008(1A), 31A. Ministry of Environment and Natural Resources, Sri Lanka
- Rafizul IM, Alamgir M (2012) Characterization and tropical seasonal variation of leachate: results from landfill lysimeter studied. *Waste Manage* 32:2080–2095
- Ramakrishnan A, Surampalli RY, Zhang TC, Tyagi RD, Kao CM (2013) New and emerging contaminants in landfill leachate and their sustainable Management, International conference on solid waste 2013: Innovation in Technology and Management, Wan Chai, Hong Kong
- Resources MoEaN (2008) National environmental (protection and quality) regulations. No. 47 OF 1980, 2008. (1A):31A
- Rivas FJ, Beltra F, Gimeno O, Acedo B, Carvalho F (2003) Stabilized leachates: ozone-activated carbon treatment and kinetics. *Water Res* 37:4823–4834
- Robinson H, Luo M (1991) Characterization and treatment of leachates from Hong Kong landfill sites. *J Instr Water Environ Manage* 5(6):326–335
- Robinson H (2007) The composition of leachates from very large landfills: an international review. *Commun Waste Resour Manage* 8(1):19–32
- Shuokr QA, Hamidi AA, Mohd SY, Mohammed JKB (2010) Leachate characterization in semi-aerobic and anaerobic sanitary landfills: a comparative study. *J Environ Manage* 91:2608–2614
- Silva AC, Dezotti M, Sant’anna GL Jr (2004) Treatment and detoxification of a sanitary landfill leachate. *Chemosphere* 55:207–214
- Steenen M (1997) Chemical oxidation for the treatment of leachate-process comparison and results from full-scale plants. *Water Sci Tech* 35(4):249–256
- Stuart ME, Gooddy DC, Kinniburgh DG, Klinck BA (2001) Trihalomethane formation potential: a tool for detecting non-specific organic groundwater contamination. *Urban Water* 3(3):173–184
- Sun B, Zhao FJ, Lombi E, McGrath SP (2001) Leaching of heavy metals from contaminated soil using EDTA. *Environ Pollut* 113:111–120
- Sundaravadeivel M, Vigneswaran S (2001) Constructed wetlands for waste water treatment. *Crit Rev Environ Sci Tech* 31(4):351–409
- Tatsi AA, Zouboulis AI (2002) A field investigation of the quantity and quality of leachate from a municipal solid waste landfill in a Mediterranean climate. *Thessaloniki Greece* 6:207–219
- Trabelsi I, Sellami I, Dhifallah T, Medhioub K, Bousselmi L, Ghrabi A (2009) Coupling of anoxic and aerobic biological treatment of landfill leachate. *Desalination* 248:185–192
- Training Module (2005) Closing an open dumpsite and shifting from open dumping to controlled dumping and to sanitary land filling, United Nations Environment Programme
- Trankler J, Visvanathan C, Kuruparan P, Tubtimthai O (2005) Influence of tropical seasonal variations on landfill leachate characteristics-Results from lysimeter studies. *Waste Manage* 25(10):1013–1020
- Trihalomethanes in Drinking-water, Background document for development of WHO Guidelines for Drinking-water Quality, World Health Organization (2004)
- Vasanthi P, Kaliappan S, Srinivasaraghavan R (2008) Impact of poor solid waste management on ground water. *Environ Monit Assess* 143:227–238

- Wang Z et al (2002) Landfill leachate treatment by a coagulation-photooxidation process. *J Hazard Mater* 95:153–159
- Welikannage K, Liyanage BC (2009) Organic waste composing by low cost semi aerobic converted trench method at Central Province. Proceedings of Annual Academic Sessions, Open University of Sri Lanka
- Weragoda SK (2005) THM formation modeling in treated water using the rapid organic characterization technique. Asian Institute of Technology
- Wijsekara SSRMDHR, Ariyawansa RTK, Madanayake N, Chandrasekara WWCK, Basnayake BFA (2010) Determination of pseudo natural attenuation of leachate emission from Gohagoda dumpsite in Kandy. 3rd International Symposium, Sabaragamuwa University of Sri Lanka
- Wijsekara SSRMDHR, Silva ND, Basnayake BFA, Vithanage M (2013) Application of resistivity imaging techniques for ground investigation and characterization of open municipal solid waste dump site in Sri Lanka. International conference on solid waste 2013: Innovation in Technology and Management, Wan Chai, Hong Kong
- William J (1997) Groundwater chemistry fundamentals and applications to contamination. 1st ed. Lewis Publishers, Washington, p 12–14
- Wimalasuriya KMDDC, Chandrathilake THRC, Liyanage BC, Gunatilake J (2011) In-situ water quality and economical leachate treatment system for Gohagoda dump site, Sri Lanka. Annual academic sessions, Open University of Sri Lanka
- Zouboulis AI, Chai XL, Katsoyiannis IA (2004) The application of bioflocculant for the removal of humic acids from stabilized landfill leachates. *J Environ Manage* 70:35–41