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MINI-REVIEW

Use of aged refuse-based bioreactor/biofilter for landfill leachate treatment

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Abstract Sanitary landfilling is a proven way for disposal of municipal solid waste (MSW) in developed countries in general and in developing countries in particular, owing to its low immediate costs. On the other hand, landfilling is a matter of concern due to its generation of heavily polluted leachate. Landfill leachate becomes more refractory with time and is very difficult to treat using conventional biological processes. The aged refuse-based bioreactor/biofilter (ARB) has been shown to be a promising technology for the removal of various pollutants from landfill leachate and validates the principle of waste control by waste. Based on different environmental and operational factors, many researchers have reported remarkable pollutant removal efficiencies using ARB. This paper gives an overview of various types of ARBs used; their efficiencies; and certain factors like temperatures, loading rates, and aerobic/anaerobic conditions which affect the performance of ARBs in eliminating pollutants from leachate. Treating leachate by ARBs has been proved to be more cost-efficient, environment friendly, and simple to operate than other traditional biological techniques. Finally, future research and developments are also discussed.

Keywords Pollutant removal · Aged refuse · Landfill leachate · ARB · Leachate treatment

Introduction

Solid waste is a growing global issue due to the continuous increase in its quantity (Cossu et al. 2003). The increasing human population, urbanization, and economic uplift are leading to an increased per capita generation of solid waste. During the last decade, municipal solid waste (MSW) production has increased about 20 %; a considerable fraction of this increase consists of household and commercial waste which is expected to increase up to 40 % until 2020 (OECD 2007). United Nations-HABITAT predicts that the production of solid waste could rise from 2.0–4.9 billion tonnes per year in 2006 to 2.4–5.9 billion tonnes per year until 2025 (UN-HABITAT 2010). According to World Bank's 2012 report, a decade ago, 2.9 billion residents used to generate about 0.64 kg of MSW per capita per day (0.68 billion tonnes per year), but now, 3 billion residents generate 1.2 kg per capita per day (1.3 billion tonnes per year). These adverse trends in waste generation demand consideration of various issues, most importantly, public health, impact on environment, and waste management (UN, 2010). Solid waste explicitly is linked to urbanization and economic development. Being world's most populated and economically fast growing country, China surpassed USA in 2004 in terms of waste generation. Until 2030, China will likely produce twice as much MSW as USA (World Bank 2012).

All over the world landfills are still the most common practice of waste disposal, especially in developing countries owing to its economic advantages and also because of its decomposition capability under controlled conditions until its eventual transformation into relatively inert and stabilized material (George et al. 1993; Christian et al. 2000; Sponza and Agdag 2004; Chai et al. 2007). Up to 95 % of total MSW collected worldwide is disposed off in the landfills (El-Fadel et al. 1997). In 2009, nearly 54 % of the 243 million tons of MSW generated in the USA were discharged to landfills (USEPA 2010), while more than 90 % of the refuse in China was discarded in landfills (Chai et al. 2007). Figure 1 illustrates the importance of landfill over other disposal routes worldwide.

Unlike in developed countries, there is a considerable dearth of scientifically engineered landfills in most

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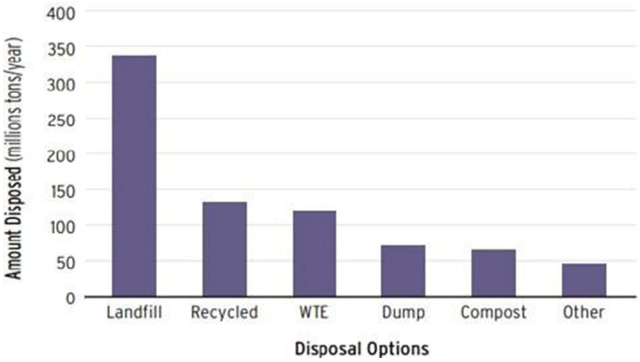


Fig. 1 Total MSW disposed of worldwide (World Bank Report 2012)

underdeveloped and developing countries; so, open dumping is frequently practiced (Singh et al. 2014). It is reported that 90 % of open dumpsites in Asia are without any precautionary measures to prevent release of greenhouse gasses (GHGs). In India alone, approximately 500 tons of CH_4 and CO_2, potent GHGs, are discharged daily from MSW dumpsites (Hebbliker and Joshua 2001). The rate of gas emission differs due to waste composition, age, quantity, moisture content, and hydrogen-to-oxygen ratio available during waste decomposition (Jha et al. 2008). Open dumpsites provide a perfect breeding ground for disease vectors and their proliferation and cause odor problems (Singh et al. 2014). If landfilling is not properly managed, it may cause potential adverse effects to the environment, including groundwater and surface water pollution, release of landfill gasses (LFGs), and dust (Kjeldsen et al. 2002; Read et al. 2001). Moreover, some of these impacts may last for centuries (Kruempelbeck and Ehrig 1999). That is why China has closed more than 1,000 landfill sites (Chai et al. 2007), and the European Union (EU) had adopted landfill directive; according to which the quantity of biodegradable MSW disposed of to landfill must be reduced to: 75 % of 1995 baseline levels by 2006, 50 % by 2009 and 35 % by 2016 (Council of the EU 1999).

In landfills, solid waste undergoes physicochemical and biological changes; as a consequence, decomposition of the organic fraction of MSW along with percolation of rainwater and moisture content of MSW leads to the production of highly contaminated liquid called “leachate” (Kurniawan et al. 2006). With the passage of time, leachate becomes mature and difficult to treat due to refractory organics. The cases of water pollution due to landfill leachate are a global issue, particularly in European countries, China, and Australia (Ngo et al. 2009). Due to its potential hazard, landfill leachate treatment is essential, so that the treated leachate can meet the standards of respective localities for discharge into receiving water bodies (Kumar and Alappat 2005).

The selection of efficient landfill leachate treatment techniques depends upon the characteristics of the leachate, i.e., technical viability and constraints, effluent, regulatory requirements, environmental impact, and cost-effectiveness of the method applied (Kurniawan et al. 2006). In recent years, many physical, chemical, and biological processes have been practiced for leachate treatment, such as air stripping (Kargi and Pamukoglu 2004), membrane separation (Primo et al. 2008), coagulation-flocculation (Maranon et al. 2008), chemical oxidation (Sun et al. 2009), and sequencing batch reactor technology (Yan and Hu 2009; Spagni and Marsilli-Libelli 2009). Due to their simplicity and low cost, biological methods are considered as more efficient for landfill leachate pollutant removal (Yang and Zhou 2008). However, many studies have also revealed that biological methods are only effective for fresh leachate and that their efficiencies are not satisfactory for mature leachate, because the latter contains a high fraction of nonbiodegradable and toxic chemicals and also has high ammonia concentrations (Renou et al. 2008). Membrane bioreactors (MBR), however, as one of the most promising biological technologies have great potential for leachate treatment (Ravindran et al. 2009; Boonyaroj et al. 2012). Moreover, adsorption, membrane filtration, and chemical precipitation are the most frequently applied and studied leachate treatment methods worldwide. So far, almost no single technique is universally applicable or highly effective for removal of recalcitrant compounds from stabilized leachate. Therefore, a combination of biological and physicochemical methods is essential for the efficient treatment of leachate (Kurniawan et al. 2006; Zhang et al. 2013).

Aged refuse bioreactor (ARB) is a new approach to treat landfill leachate based on the principle of waste control by waste (Zhao et al. 2002); it is also an efficient and proven technique to treat sanitary wastewater, coking wastewater, livestock waste, poultry waste, phenolic compounds, and heavy metals (Zhao and Shao 2004; Wang et al. 2012). As the construction of new landfills is not an easy task, it is quite feasible to reclaim and excavate aged refuse from landfills to utilize for leachate treatment. The reclaimed material (aged refuse) can also be used as landfill cover, construction fill, and also as packing material for biofilters to treat various wastewaters (US EPA 1997; Zhao et al. 2006).

This review summarizes ARB-related research from original research papers, case studies, and review articles, including the various types of ARBs used and their efficiencies in removal of various organic, inorganic, and recalcitrant pollutants from the leachate. Moreover, the future research and development are also pointed out. To the best of our knowledge, it is the first review on this topic so far.

Composition and characteristics of leachate

Leachate is highly variable and heterogeneous. Generally, leachate contains a huge quantity of dissolved organic matter and inorganic macro-compounds like ammonia-nitrogen, calcium (Ca), magnesium (Mg), manganese (Mn), Chloride (Cl^-), sulfate (SO_4^{2-}), and hydrogen carbonate (HCO_3^-) and heavy metals (Renou et al. 2008; Kjeldsen et al. 2002). Dissolved organic matter is a main composition of leachate and consists of variety of compounds, ranging from simple volatile fatty acids (VFAs) to high molecular weight compounds including aromatic hydrocarbons, phenols and chlorinated aliphatic, and fulvic and humic substances (Mohobane 2008; Wiszniowski et al. 2006).

However, the characteristics of landfill leachate can usually be represented by basic parameters like biochemical oxygen demand (BOD), chemical oxygen demand (COD), pH, suspended solids (SS), total nitrogen (TN), ammonium nitrogen (NH_4^+-N), ammonia nitrogen (NH_3-N), nitrate nitrogen (NO_3^--N), total phosphorus (TP), and heavy metals (Kjeldsen et al. 2002). Leachate generation also varies as a function of the successive aerobic, acetogenic, methanogenic, and stabilization stages in the landfills (Walender et al. 1997). Table 1 demonstrates three types of leachates according to landfill age. Normally, young landfill leachates (less than 5 years) contain large amounts of biodegradable organic matter, and in a mature landfill (more than 10 years), the organic fraction of the leachate becomes dominated by refractory compounds (Harsem 1983; Walender et al. 1997; Wang et al. 2003).

Leachate discharge standard

Currently, the quality of landfill leachate effluent has to comply with increasingly stringent discharge standard. Several countries and regions have their own leachate discharge standard set by their own regulatory agencies. Table 2 lists permissible discharge limits in various countries worldwide. The variation in standard limit values of different regions might be due to certain environmental and economic conditions, as well as the technology used to treat landfill leachate.

The removal of organic substances based on total organic carbon (TOC), COD, BOD, and ammonium from leachate is the general prerequisite before discharging the leachates into natural waters. Toxicity analysis has confirmed the potential environmental and health dangers of landfill leachates and the necessity to treat it so as to meet the standard guidelines (Silva et al. 2004; Ngo et al. 2009).

Characteristics of aged refuse

Relative to young refuse landfill, the organic fraction of the leachate is lower in the mature one; the refuse landfill reaches a stabile state after 8–10 years, and the consequently mature waste is called *aged refuse* (AR). It has little volumetric weight, high porosity, high organic content, cation exchange, and adsorption ability; moreover, it contains a significant spectrum of microbes having significant degradation capability for both biodegradable and refractory organic matter (Zhao et al. 2002, 2006, 2007). AR has special characteristics different from other biological media like activated sludge, etc. The appropriate porosity in AR contributes high permeability which may prevent fouling during leachate treatment operation (Li et al. 2009); moreover, it is suitable for good AR structure, aeration, water infiltration, and microbial growth (Sachs 1999).

Types of ARBs and process configurations

The setup of the ARB is similar to that of a trickling filter, which supports bacterial-attached growth while allowing wastewater to trickle down due to gravity (Langwaldt and Puhakka 2000). Typically, support materials like lumps of crushed rocks, slag or pumice, and plastic fills are used in trickling filters, while aged refuse is the media of ARB. Moreover, unlike trickling filters, ARBs generate less sludge and do not need a secondary sedimentation unit for sludge removal (Wang et al. 2007).

Various researchers used different types of ARBs and process configurations (Zhao et al. 2002, 2007; Chen et al. 2009; Xie et al. 2010, 2012, 2013; Sun et al. 2011; Han et al. 2013). Most laboratory-scale reactors were round- or cylindrical-shaped for easy water distribution, while rectangular- or square-shaped reactors were used in pilot-scale experiments because they are easy to construct and run. The height and inner diameter of reactors used in lab-scale experiments ranged from 80 to 150 and 20 to 80 cm, respectively. Li et al. (2009) used a field-scale bioreactor with 3-m height and 45-m width, having a carrying capacity of 7000 m^3 aged refuse and leachate loading rate of 50 m^3/day. Wang et al. (2014) studied a full-scale three-stage horizontal and tower ARBs; in the horizontal ARB, the height of each bioreactor was about 3 m, and area of the first bioreactor was 2,300 m^2, while the second and third was 2,000 m^2 each. The vertical height of each tower ARB bed was approximately 1 m. Leachate was pumped and sprayed over the first tower bed which trickled down to the rest of the beds under gravity.

Performance of ARB on leachate treatment

Recently, ARB proved to be a promising technology for removal of various pollutants from leachate. Table 3 shows the efficiency of ARBs for the removal the organic, nitrogenous, and total phosphorus like COD, BOD_5, TN, NH_3-N, NH_4^+-N, and TP, from different landfill leachates. Using ARB, 64–99 % COD, >90 % BOD_5 and TP, 49–95 % TN,

Table 1 Landfill leachate classification versus age (Renou et al. 2008; 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 (mg/L)	10,000 -20,000	–	50–100
TOC (mg/L)	9,000 – 15,000	–	100–1,000
BOD/COD	>0.3	0.1–0.3	<0.1
Organic compounds (%)	80 % VFA*	5–30 % VFA+humic and fulvic acids	Humic and fulvic acids
VFA (as acetic acid), mg/L	9,000 - 25,000	–	50–100
Heavy metals (mg/L)	>2	<2	<2
Biodegradability	High	Medium	Low

* *VFA* volatile fatty acid

89–99.9 % NH_3-N, and 66–99.8 % NH_4^+-N were removed from the leachate influent.

Removal of color and suspended solids

Many researchers have observed significant reduction in color, odor, and suspended solids after leachate had passed through the ARBs; their removal being mostly caused by the filtering and absorption effect of the aged refuse. Li et al. (2009, 2010) reported significant reduction in color, i.e., from 1,500 to less than 200 (Pt/Co degree), and found that the final effluent was inodorous and pale yellow in color. Lei et al. (2007) also observed that after treatment, the original malodorous black leachate had become inodorous and pale yellow. Moreover, the concentration of SS in the influent was reduced from 11,400–14,700 to 300–398 mg/L and from 2,324–4,710 to below 150 mg/L, respectively. Erses et al. (2008) reported removal of the total suspended solids (TSS) of more than 97 % to an effluent concentration of 300–385 mg/L, while 92–96.4 % color was also removed from the leachate influent.

Removal of organic pollutants (COD, BOD, TOC)

The composition and concentration of organic matter in the influent varies significantly due to variation in climatic conditions and practical operations of landfills (Li et al. 2010). COD and BOD_5 are often used to determine the degree of degradation of MSW. In a pilot-scale horizontal ARB, Wang et al. (2014) removed more than 97.6 % BOD_5 and an average 90 % COD at influent concentrations of 277–362 and 2,323–2,754 mg/L respectively. Most of the organic compounds were removed in the first bed followed by the second and third beds.

Using a 100-m^3 leachate/day capacity ARB, Li et al. (2010) attained 64–93 % COD and 95.8–99.8 % BOD_5 removal efficiency to a BOD_5/COD ratio lower than 0.03. Similar results were reported by Zhao et al. (2002) who found COD and BOD_5 removal from initial levels of 3,000–7,000 and 540–1,500 to 100–350 and 10–200 mg/L, respectively, having 90–99 % efficiency at a loading rate of 80–200 l/m^3 refuse/day. The final BOD_5/COD ratio less than 0.1–0.2 indicated that the biodegradable fraction of the effluent COD was low. Erses et al. (2008) claimed to remove more than 90 % of COD within 70 days using three-stage aerobic bioreactor

Table 2 Maximum leachate discharge limits (Cao et al. 2001; Qzturk et al. 2003; Kurniawan et al. 2006; Fan et al. 2007; Bohdziewicz et al. 2008; National Emission Standards of China 2008).

Country parameter	China	Hong Kong	Vietnam	Germany	France	South Korea	Turkey	Taiwan	Poland	UK
COD	100	200	100	200	120	50	100	200	125	–
BOD_5	30	800	50	20	30	–	50	–	30	60
SS	30	–	–	–	–	–	100	50	–	–
NH_4-N	25	5	–	–	5	50	–	–	10	–
PO_4-P	3.0*	25	6	3.0*	25	–	1.0*	–	–	–
TKN	40	100	60	70	30	150	–	–	–	–

All above values are in milligrams per liter

* *TP* total phosphorus

Table 3 Pollutant removal efficiency by ARB

Operating conditions	Maximum pollutant removal efficiency (%)						
	COD	BOD_5	TN	NH_3-N	NH_4^+-N	TP	References
Temperature n.c HLR: 100 m^3/day	64	95.8–99.8	49-63	–	96.9-99.8	–	Li et al. (2010)
Temperature 30–35 HLR 10.5 L/m^3/day	96.61	–	95.46	–	–	–	Han et al. (2013)
Temperature r.t HLR 20 L m^3/day	80	>90	–	89	–	96	Xie et al. (2010)
Temperature 30±1 NLR 0.74 g/kg/day	–	–	>90	–	–	–	Xie et al. (2013)
Temperature n.c HLR 80–200 L/m^3/day	90–99	90–95	20–30	99.5	–	–	Zhao et al. (2002)
Temperature n.c HLR 80–200 L/m^3/day	87.8–96.2	94.7–97.3	58–73	–	96.9–99.4	–	Li et al. (2009)
Temperature 20 HLR 20 L m^3/day	59±4.3	91±1.5	60±3.8	–	66±6.6	95±4.3	Xie et al. (2012)
Temperature n.c HLR 40 L/m^3/day	90.9	–	–	98.9	–	–	Wang et al. (2009)
Temperature 20–30 HLR 10–20 L/m^3/day	90	97.6	81	–	99.3	–	Wang et al. (2014)
Temperature r.t HLR 100 m^3/day	98.5	99.9	64.2	99.9	–	–	Lei et al. (2007)

All temperatures are in degree Celsius (°C)

HLR hydraulic loading rate, *NLR* nitrogen loading rate, *n.c* not controlled, *r.t* room temperature

compared to 462 days needed in an anaerobic bioreactor. TOC with initial concentration of 1,438 mg/L was reduced to 218 mg/L in 374 days while further decreased to 290 mg/L in 630 days operation period. BOD removal showed the same trend, while BOD_5/COD ratio in an operation period of 372 days declined to 0.03 at the end of the experiment.

Stabilized landfill leachate has a BOD_5/COD level of less than 0.1. This can be interpreted with a BOD_5 value of less than 10 mg/L and a COD less than 100 mg/L (Kjeldsen et al. 2002; Borglin et al. 2004). A low BOD_5/COD ratio indicates that leachate is low in biodegradable organic carbon and relatively high in refractory organic compounds such as humic substances (Erses et al. 2008). Table 4 shows the average influent and effluent levels of COD, BOD_5, and BOD_5/COD ratio. The effluent BOD_5/COD ratio ranged from 0.03 to less than 0.2, which indicates good efficiency of ARB in removing organic pollutants from leachate, particularly for those experiments which were performed comparatively in minimum operation periods.

Nitrogen removal

Ammonia removal

Removal of ammonia from leachate is necessary because of its toxic effects to water bodies and its BOD in receiving waters. In landfill leachate, the vast majority of the ammonia-nitrogen species are in the form of ammonium ion (NH_4^+) because pH levels are generally less than 8.0. Dissolved unionized ammonia is more toxic to anaerobic degradation processes than ammonium ions but should not be present in significant concentrations in a landfill leachate (Berge and Reinhart 2005).

Wang et al. (2014) successfully removed an average 99.3 % NH_4^+-N at influent concentration of 1,237–1,506 mg/L. Like organic compounds, removal occurred mostly in the first stage bioreactor and during the entire period it could meet 25 mg/L, i.e., National Emission Standards China (GB 16889-2008). The ammonia-nitrogen removal efficiency in a bioreactor

Table 4 Organic pollutant removal efficiency of ARB

	Operation period	Influent BOD_5	Effluent BOD_5	Influent COD	Effluent COD	Influent BOD_5/COD	Effluent BOD_5/COD	References
1	182	611.5	07	2,557	317	0.24	0.03	Li et al. (2010)
2	547	1,388	54	8,160	643.5	0.17	0.08	Li et al. (2009)
3	180	450	25	5,800	520	0.09	0.04	Xie et al. (2010)
4	365	2,040	105	5,000	225	0.4	<0.1–0.2	Zhao et al. (2002)
5	374	–	–	17,900	678	–	0.03	Erses et al. (2008)

Operation period is in days; all BOD_5 and COD values are in milligrams per liter except BOD_5/COD which is dimensionless described in our own study (Xie et al. 2013) reached 96 %, which is similar to removal efficiencies reported by Zhao et al. (2002) and Xie et al. (2012); however, a higher efficiency of NH_3-N removal (99.45 and 75 %) has been achieved by Sun et al. (2011) using a fresh refuse bioreactor in an alternating semi-aerobic and anaerobic conditions, respectively. It shows that semi-aerobic recirculation is more effective to eliminate NH_3-N than a strict anaerobic recirculation process. In lab-scale nitrogen removal studies, many researchers (Bilgili et al. 2007; Berge et al. 2006; Xie et al. 2010; Huo et al. 2008; Onay and Pohland 1998) have also argued that ammonia needs to be partially oxidized first before it can be eliminated, and this oxidation is a biological process requiring aerobic conditions.

More than 98 % NH_3-N was eliminated using a three-stage pilot-scale ARB when 50 m^3/day influent leachate was pumped and sprayed over surface of three stages with the same frequency (10 times per day, each time spraying for 5 min). The ammonia concentration in the first stage, second stage, and third stage effluent were 110–434, 68–194, and 6–45 mg/L, respectively, showing a strong nitrification capability of the ARB (Li et al. 2009).

As shown in Fig. 2a, Li et al. (2010) also observed the influent ammonia having concentration 538–1,583 mg/L decreased sharply to 17–774 mg/L after treatment of first-stage ARB. The second stage effluent remained almost the same range (at 2–19 mg/L) with removal efficiency of 96.9–99.8 %. It should be noted that 100 m^3/day influent leachate was sprayed over the surfaces of two stages with the same frequency (10 times per day, each time for 30 min). On the other hand, most NH_4^+-N in the leachate was converted to NO_2-N in the first-stage ARB (Fig. 2b) and subsequently to NO_3-N later in the second-stage ARB (Fig. 2c). This illustrates the strong nitrification capability of ARB for ammonia. The prevalence of nitrification process reflects the activity of nitrifying microbial populations in the ARB.

Chen et al. (2009) operated three reactors filled with 1-year-old refuse (R1), 6-year-old refuse (R6), and 11-year-old refuse (R11), while nitrate solution (1000 mg NO_3-N/L) was added into each reactor. The results showed that all the reactors were able to consume nitrate; however, R1 had comparatively high rate of nitrate degradation and N_2 concentration. This implies that the content of organic matter in R1 was higher than in R6 and R11. The behavior of N_2 in R1 and R6 and the presence of N_2O in R11 were indicative for the occurrence of denitrification. Denitrification may occur most efficiently in young waste rather than older one because denitrifiers require a sufficient organic carbon source for high nitrate removal rates. If sufficient organic carbon is not readily available, partial denitrification may occur, which might lead to generation of toxic intermediates (N_2O and NO) which are known GHGs (Cheng et al. 2004; Khalil et al. 2004).

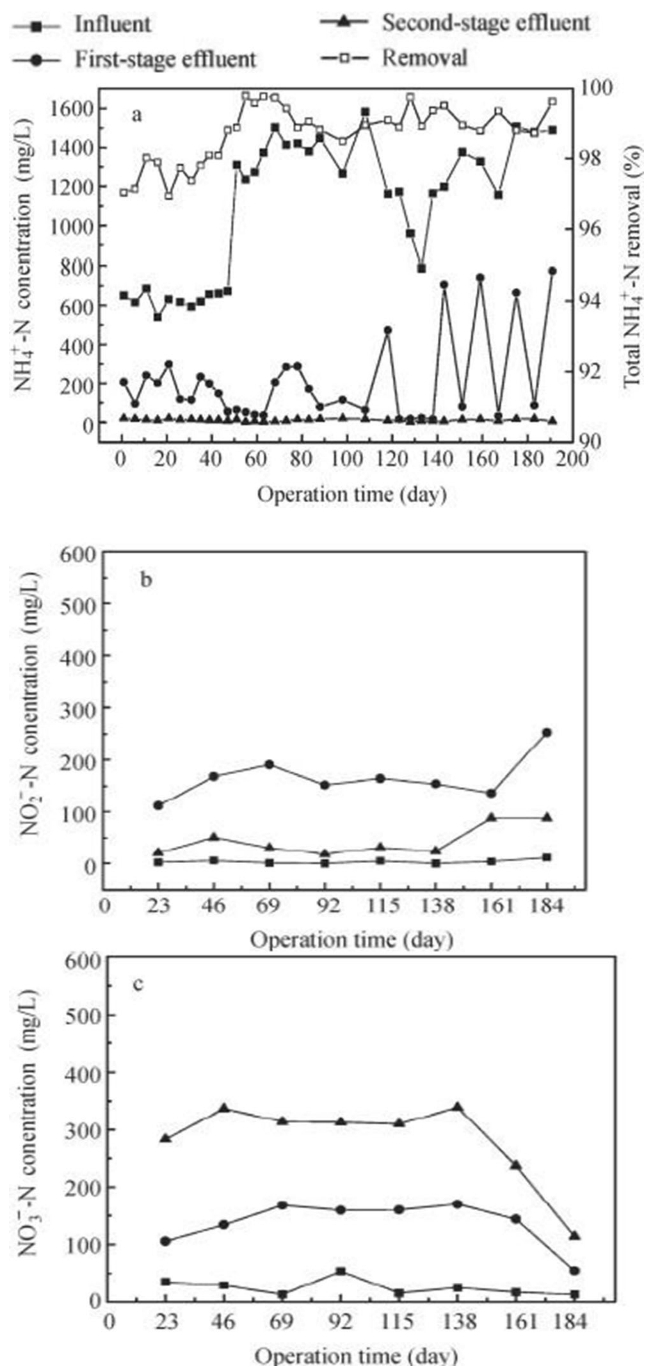


Fig. 2 N pollutant concentration in influent and effluent: **a** NH_4-N concentrations and total NH_4-N removal; **b** NO_2-N concentrations of influent and two-stage effluent; **c** NO_3-N concentrations of influent and two-stage effluent (This figure has been used after getting consent from the author.)

Total nitrogen removal

Biological nitrification/denitrification is commonly used for removal of nitrogen in leachate treatment (Giannis et al. 2008). Xie et al. (2012) noticed that the TN removal reached the highest level of 70 % in the start-up phase but decreased later to about 50 %, which was lower than for other pollutants.

The reason might be the weak denitrification effect caused by lower COD/TN ratio of the influent, where there was not sufficient utilized carbon source for denitrification. The higher TN removal rate in the first 4–5 weeks showed the probability of existence of other nitrogen removal pathways in the biofilter or maybe there was initially still sufficient organic carbon as source of reducing equivalents.

Han et al. (2013), using semi-aerobic aged refuse biofilter (SAARB), found TN removal efficiency of 95.46 % which was significantly higher than reported for a tower ARB (21.5–65.2 %; He et al. 2007) and a multistage ARB (58–73 %; Li et al. 2009).

Xie et al. (2013) found that high nitrogen removal rate in ARB could not be explained simply by nitrification and denitrification process. Ammonia oxidation, denitrification, and anammox (anaerobic ammonium oxidation) are also possible pathways and could work simultaneously to remove nitrogen in the ARB. About 10 % of TN was removed by anammox, and the anammox bacterium *Candidatus Kuenenia stuttgartiensis* was detected in the lab-scale ARB (Wang et al. 2013), supporting that nitrogen was removed through different pathways in this ARB. The highest nitrogen removal efficiency to be reached was 95 %, but efficiency decreased to 62.2 % when nitrogen loading rate (NLR) increased, while others also reported fluctuating TN removal efficiencies from 49 to 90 % (Li et al. 2010; Song et al. 2011), suggesting that TN removal in ARB is very sensitive to the influent loading.

Total phosphorus removal

In lab-scale and pilot-scale ARB experiments where the TP level of influent ranged from 10 to 25 mg/L, the effluent concentration was greatly reduced to 1 mg/L, below the national standard emission limit for China (See Table 2); hence, no further treatment was necessary. The average TP removal efficiency was 96 % (Xie et al. 2012).

The TP concentration in an aerobic bioreactor having fresh refuse (F2) decreased to 31 mg/L from an influent concentration of 76 mg/L, whereas the TP concentration in semi-aerobic bioreactor with fresh refuse (F1) declined sharply from 138 to 5 mg/L at the beginning of the experiment after 87 days. The TP concentration in F1 fluctuated between 1 and 3 mg/L until the end of the experiment (Sun et al.2011). On the contrary, Jiang et al. (2007) claimed that TP concentration increased first followed by stabilization at a constant level of 20–30 mg/L and concluded that anaerobic bioreactor landfills were capable to only very minor or no phosphorus removal efficiency. Aeration has positive effect on the removal of orthophosphate in bioreactor landfill (Erses et al. 2008; Sun et al. 2011).

Removal of heavy metals

Heavy metals in landfill leachate are present as micro pollutants, and their subsequent leaching to groundwater is in trace concentrations. Nevertheless, release of these compounds from landfill leachate to groundwater may potentially be of an environmental concern (Varank et al. 2011) due to their nonbiodegradability, toxicity, and consequent persistence (Dutta 2002). As shown in Table 5, Zhang et al. (2013) found different heavy metals like Pb, Zn, Fe, and Mn in alarming concentrations, while Xie et al. (2010) noted copper (Cu) higher than the National Emission Standard, China.

Like for other pollutants, no systematic research has been done on the removal of heavy metals in ARBs. However, Wang et al. (2012) have evaluated the efficiency of ARB for the removal of hexa chromium Cr (VI) from simulated wastewater. In the experiment, column I reactor was filled with unpasteurized AR while column II with pasteurized AR. In column I, the total chromium and Cr (VI) was 179.58 and 15.30 mg/kg, respectively, while in column II, 161.94 mg/kg was total chromium and nearly 19 mg/kg Cr (VI). The Cr (VI) removal trend was better in unpasteurized AR, which means certain microbes found in AR had made a contribution to its removal.

Factors affecting performance of ARBs

Effects of hydraulic loading rate

The hydraulic loading rate (HLR) has a considerable effect on the performance of ARBs. Xie et al. (2010) demonstrated 89 and 98 % of COD and ammonia removal, respectively, with 4 l m^3/days HLR, but for the sake of economy, the HLR of 20 l m^3/days was chosen for the subsequent experiment which showed 75 % of COD and 90 % ammonia removal, similar to that of Zhao et al. (2002). Xie et al. (2012) also noticed an increase in effluent COD concentration with increasing HLR from 20 to 40 l m^3/days. The reason might be higher HLR brought more nonbiodegradable substances which lead to increase the effluent COD. The same results appeared when Zhao et al. (2007) introduced sewage into the ARB at a wet/dry ratio of 1:5 and a continuous introduction time of 8 h with a periodic term of 2 days.

As shown in Fig. 3, our previous work (Xie et al. 2013) has shown the performance of bioreactor at different NLR. In the first operation stage, the TN removal efficiency of influent at NLR 0.74 g (TN)/kg (vs) day was 96.6 % but decreased to 88.5 % at 0.95 g (TN)/kg/day NLR at second stage, while in the fourth stage, on increasing NLR (2.03 g/kg/day), the nitrogen removal efficiency also decreased to 65 %. This trend clearly illustrates that loading rate affects the efficiency of ARB to remove various pollutants; therefore, maintenance

Table 5 Heavy metal in different landfill leachate

Age (years)	Landfill site	Cd	Cr	Cu	Pb	Zn	Ni	Fe	Mn	References
O	Shanghai, China	0.006	0.08	0.12	0.10	1.12	0.2	–	–	Xie et al. (2012)
O	Piskornica, Croatia	–	0.016	0.47	0.003	0.63	0.023	2.017	–	Vrhovac et al. (2013)
O	Shanghai, China	0.02	0.11	0.82	0.25	0.94	0.95	–	–	Chai and Zhao (2006)
O	Zhejiang, China[a]	0.24	0.31	0.74	4.56	532.5	0.2	15.47	2.39	Zhang et al. (2013)
O	Wysieka, Poland	0.009	0.06	0.03	BDL	0.29	BDL	–	–	Kulikowska and Klimiuk (2008)
Y	Zhejiang, China[a]	0.01	0.17	0.18	0.01	17.21	0.06	1.94	0.54	Zhang et al. (2013)
Y	Zhejiang, China[a]	0.6	0.78	1.85	11.39	1,331.25	0.512	38.67	5.98	Zhang et al. (2013)
I	Pennsylvania, USA	–	0.8	0.1	–	0.4	–	5.2±0.8	0.2±0.1	Zhao et al. (2012)
I	Hampshire, USA	–	0.3	0.1	–	0.1	–	3.1±0.9	0.2	Zhao et al. (2012)

All above values are in milligrams per liter

BDL below detection limit, *O* old, *Y* young, *I* intermediate

[a] Leachate samples were collected from three different landfills simultaneously

of lower NLR in the ARB is vital for adequate TN removal in practical operations.

Effects of temperature

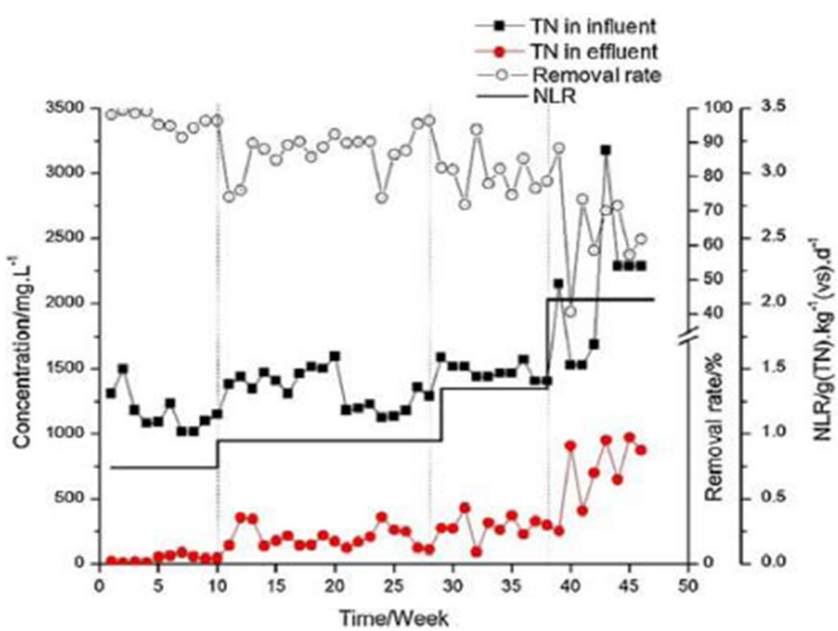
The removal efficiency of pollutants also decreases with decreasing temperatures. Xie et al. (2012) observed that the efficiency of pollutant removal decreased sharply when temperature was decreased from 20 to 10 °C. Zhao et al. (2002) also noticed such a trend in that the effluent quality in winter (at temperature 0–10 °C) was slightly lower than in summer (25–37 °C). The biggest challenge for the leachate treatment with outdoor ARB is the low temperature in winter where microbial activities are relatively low (Renou et al. 2008). Effluent recirculation might be an alternative solution in order to achieve the required efficiency of ARB at low temperatures (Xie et al. 2013). In an onsite experiment, Xie et al. (2012) observed that underground pilot-scale bioreactor could maintain a reactor temperature of 17 °C in the cold season which was beneficial to TN and TP removal of landfill leachate.

The stabilization process of refuse is quite different in different regions and locations of landfills. In humid and warm areas, refuse is highly stabilized, whereas in dry and cold areas, the stabilization period for landfill refuse is much longer; hence, refuse with longer placement has to be taken as biofilter packing material (Zhao et al. 2002).

Effects of aerobic and anaerobic conditions

Aerobic bioreactors have proved to be ideal in terms of pollutant removal with leachate reduction and odorless condition (Berge et al. 2005). In a study, over 93 % COD removal

Fig. 3 TN in the influent and effluent at different nitrogen loading rates



was claimed, plus an increase in DO after passage through a 150-cm high bioreactor (Zhao et al. 2007). Using SAARB, Han et al. (2013) reported aerobic-anoxic-anaerobic zone formation simultaneously which is a favorable condition for microbial growth and decomposition of organic matter and nitrogenous pollutants. Aerobic zones are found at the top and the bottom of the reactor, while the anaerobic zone is located in the middle of bioreactor (Zhao et al. 2002; Han et al. 2013). The average removal efficiency of SAARB was significantly higher than of any other biofilters. When two fresh refuse bioreactors under semi-aerobic and anaerobic conditions were operated, the aerobic condition was a promising approach for refuse management and leachate treatment (Sun et al. 2011).

In case of mature leachate, alternating aerobic and anaerobic zones help to improve nitrogen removal since this creates ideal conditions for denitrification and anammox bacteria. In a field-scale ARB with alternative aerobic and anaerobic environments, the different nitrogen functional genes *amoA*, *nirS*, and anammox 16S ribosomal RNA (rRNA) gene were found to exist simultaneously in the bioreactor, and the coexistence of multiple nitrogen removal pathways in the ARB led to better nitrogen removal performance (Wang et al. 2014).

Conclusion and future perspectives

The successful application of ARB achieves the principal of waste control by waste and provides a feasible option to treat landfill leachate. It is a promising biological and physicochemical process that has been proven to be technically feasible and economically favorable while having the capability to treat various organic pollutants, nitrogenous compounds, total phosphorus, and might even be used for removal of heavy metals. Like any other biological treatment process, the loading rate, temperature, aerobic and anaerobic conditions, etc. have clear impacts on the efficiency of ARB to treat leachate. Increasing temperature and lower HLR proved to be favorable for more complete pollutant removal. Moreover, alternating aerobic-anoxic-anaerobic zones in the biofilter improve removal efficiency for some pollutants like nitrogen.

Despite good results obtained by ARBs for the removal of various pollutants from landfill leachate at the laboratory and pilot scale, research at the full scale is still needed to eliminate shortcomings and further develop better ways to deal with recalcitrant compounds. Combining ARB with certain chemical methods like chemical precipitation, advance oxidation process, electrochemical process, etc. may further improve the removal efficiency of recalcitrant compounds present in leachate. Moreover, study of the functional bacterial community to reveal the ARB mechanism and practical applications might be a significant step toward leachate management and treatment. Furthermore, paying more attention on using ARB for treatment of xenobiotic and refractory compounds can be future research perspectives.

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References

Berge ND, Reinhart DR (2005) The fate of nitrogen in bioreactor landfills. Crit Rev Environ Sci Technol 35:365–399

Berge ND, Reinhart DR, Dietz J, Townsend T (2006) *In situ* ammonia removal in bioreactor landfill leachate. Waste Manag 26:334–355

Bilgili MS, Demir A, Ozkaya B (2007) Influence of leachate recirculation on aerobic and anaerobic decomposition of solid wastes. J Hazard Mater 143:177–183

Bohdziewicz J, Neczaj E, Kwarciak A (2008) Landfill leachate by means of anaerobic membrane bioreactor. Desalination 221:559–565

Boonyaroj V, Chiemchaisri C, Chiemchaisri W, Theepharaksapan S, Yamamoto K (2012) Toxic organic micro-pollutants removal mechanisms in long-term operated membrane bioreactor treating municipal solid waste leachate. Bioresour Technol 113:174–180

Borglin SE, Hazen TC, Oldenburg CM, Zawislanski PT (2004) Comparison of aerobic and anaerobic biotreatment of municipal solid waste. J Air Waste Manag Associ 54:815–822

Cao HT, Nguyen HD, Nguyen QH, Truong LP, Nguyen HK, Duong DT, Nguyen TV, Nguyen AT, Nguyen TD (2001) Study on treatment of the leachate from landfill site. In: Namson and Socon (eds) Hanoi, Japan, pp 154-162

Chai X, Zhao Y (2006) Adsorption of phenolic compounds by aged refuse. J Hazard Mater B137:410–417

Chai X, Shimaoka T, Xiaoyan C, Qing G, Zhao Y (2007) Characteristics and mobility of heavy metals in an MSW landfill: implications in risk assessment and reclamation. J Hazard Mater 144:485–491

Chen YX, Wu SW, Wu WX, Sun H, Ding Y (2009) Denitrification capacity of bioreactors filled with refuse at different landfill ages. J Hazard Mat 172:159-165

Cheng W, Tsuruta H, Chen G, Yagi K (2004) N_2O and NO production in various Chinese agricultural soils by nitrification. Soil Bio Biochem 36:953–963

Christian G, Jette B, Christensen JB, Jensen DL, Kjeldsen P, Ostfeldt P (2000) Organic halogens in landfill leachates. Water, Air, Soil Pollut 120:331–345

Cossu R, Raga R, Rossetti D (2003) The PAF model: an integrated approach for landfill sustainability. Waste Manag 23(1):37–44

Council of the EU (1999) Council Directive 1999/31/EC of 26 April 1999 on landfill of waste (Landfill Directive). Council Directive 1999/31/EC

Dutta S (2002) Environmental treatment technologies for hazardous and medical wastes (remedial scope and efficacy). Tata McGraw-Hill, New Delhi

El-Fadel M, Findikis AN, Leckie JO (1997) Environmental impacts of solid waste landfilling. J Environ Manag 50:1–25

Erses AS, Onay TT, Yenigun O (2008) Comparison of aerobic and anaerobic degradation of municipal solid waste in bioreactor landfills. Bioresour Technol 99:5418–5426

Fan HJ, Chen IW, Lee MH, Chiu T (2007) Using FeGAC/H_2O_2 process for landfill leachate treatment. Chemosphere 67:1647–1652

George T, Hilary T, Samuel AV (1993) Integrated solid waste management: engineering principals and management issues. McGraw-Hill Science Engineering, Washington DC, pp 223–226

Giannis A, Makripodis G, Simantiraki F, Somara M, Gidarakos E (2008) Monitoring operational and leachate characteristics of an aerobic simulated landfill bioreactor. Waste Manag 28:1346–1354

Han ZY, Liu D, Li QB (2013) A removal mechanism for organics and nitrogen in treating leachate using a semi-aerobic aged rfuse biofilter. J Environ Manag 114:336–342

Harsem J (1983) Identification of organic compounds in leachate from a waste tip. Water Res 17:699–705

He Y, Zhao Y, Chai X, Pan Z, Zhou H, Yan D (2007) Aged refuse filled tower bioreactor for treatment of municipal landfill leachate. Environ Poll Contr. 29:502-505 (In Chinese with English abstract)

Hebbliker S, Joshua V (2001) "How well equipped are we?" Deccan Herald http://www.eolss.net

Huo SL, Xi BD, Yu HC, Fan SL, Su J, Liu HL (2008) In situ simultaneous organics and nitrogen removal from recycled landfill leachate using an anaerobic-aerobic process. Bioresour Technol 99:6456–6463

Jha AK, Sharma C, Singh N, Ramesh R, Gupta PK (2008) Greenhouse gas emissions from municipal solid waste management in Indian mega cities: a case study of Chennai landfill sites. Chemosphere 71: 750–758

Jiang J, Yang G, Deng Z (2007) Pilot scale experiment on anaerobic bioreactor landfills in China. Waste Manag 27:893–901

Kargi F, Pamukoglu MY (2004) Adsorbent supplemented biological treatment of pre-treated landfill leachate by fed-batch operation. Bioresour Technol 94:285–291

Khalil K, Mary B, Renault P (2004) Nitrous oxide production by nitrification and denitrification in soil aggregates as affected by O_2 concentration. Soil Bio Biochem 36:687–699

Kjeldsen P, Barlaz MA, Rooker AP (2002) Present and long-term composition of MSW landfill leachate: a review. Crit Rev Environ Sci Technol 32:297–336

Kruempelbeck I, Ehrig HJ (1999) Long term behavior of municipal solid waste landfills in Germany. In: Chrstensen, TH, Cossu R, Stegmann R. (Eds) Proceedings Sardinia 99, Seventh Int'l.

Kulikowska D, Klimiuk E (2008) The effects of landfill age on municiple leachate composition. Bioresour Technol 99(13):9581–9585

Kumar D, Alappat BJ (2005) Analysis of leachate pollution index and formulation of sub-leachate pollution indices. Waste Manag Res 22: 230–239

Kurniawan TA, Lo WH, Chan GYS (2006) Physico-chemical treatments for removal of recalcitrant contaminants from landfill leachate. J Hazard Mater B129:80–100

Langwaldt JH, Puhakka JA (2000) Onsite biological remediation of contaminated groundwater; a review. Environ Pollut 107:187–197

Lei Y, Shen Z, Huang R, Wang W (2007) Treatment of landfill by combined aged refuse bioreactor and elector-oxidation. Water Res 41:2417–2426

Li H, Zhao Y, Lei S, Gu Y (2009) Three stage aged refuse biofilter for the treatment of landfill leachate. J Environ Sci 21:70–75

Li H, Gu Y, Zhao Y, Wen Z (2010) Leachate treatment using a demonstration aged refuse biofilter. J Environ Sci 22:1116–1122

Maranon E, Castrillon L, Fernandez-Nava Y, Fernandez-Mendez A, Fernandez-Sanchez A (2008) Coagulation-flocculation as a pre treatment process at a landfill leachate nitrification-denitrification plant. J Hazard Mater 156:538–544

Mcbean EA, Rovers FA, Farquhar GJ (1995) Solid waste landfill engineering and design. Prentice Hall PTR, New Jersey, USA

Mohobane T (2008) The characteristics and impacts of landfill leachate from Horotiu, New Zealand and Maseru, Lesotho: a comparative study. Master thesis, University of Waikato

National Emission Standard, China (GB 16889-2008) Standard for pollution control on the landfill site of municipal solid waste. http://kjs.mep.gov.cn/hjbhbz/bzwb/gthw/gtfwwrkzbz/200804/W020110613562324914916.pdf

Ngo HH, Guo W, Xing W (2009) Water and waste water treatment technologies. In: Vigneswaran S (V) (ed) Encyclopedia of life support systems (EOLSS), Developed under the auspices of the UNESCO, vol 2. EOLSS Publishers, Oxford, pp pp. 199–pp. 257

OECD (2007) Environmental data 2007, Compendium 2006-2007. http://unstatus.un.org/unsd/ENVIRONMENT/wastetreatment.htm (Accessed Dec 2007)

Onay TT, Pohland FG (1998) In situ nitrogen management in controlled landfills. Water Res 32:1383–1392

Primo O, Rueda A, Rivero MJ, Ortiz I (2008) An integrated process, Fenton reaction–ultrafiltration, for the treatment of landfill leachate: pilot plant operation and analysis. Ind Eng Chem Res 47:946–952

Qzturk I, Altinbaas M, Koyuncu I, Arikan O, Gomec YC (2003) Advanced physicao-chemical treatment experiences on young municipal landfill leachates. Water Manag 23:441–446

Ravindran V, Tsai HH, Williams MD, Pirbazari M (2009) Hybrid membrane bioreactor technology for small water treatment utilities: process evaluation and primordial considerations. J Membrane Sci 344:39–54

Read AD, Hudgins M, Harper S, Phillips P, Morris J (2001) The successful demonstration of aerobic landfilling: the potential for more sustainable solid waste management approach? Resour, Conserv Recycl 32:115146

Renou S, Givaudan JG, Poulania S, Dirassouyanb F, Moulin P (2008) Landfill leachate treatment: a review and opportunity. J Hazard Mater 150:468–493

Sachs PD (1999) Edaphos: Dynamics of a natural soil system (2nd edition). The Edaphic Press, Newbury, pp 152–153

Silva AC, Dezotti M, Sant'Anna GL Jr (2004) Treatment and detoxification of a sanitary landfill leachate. Chemosphere 55:207–214

Singh P, Joseph K, Nagendran R (2014) Breaking the climate change municipal solid waste dump nexus—a case study in Chennai, India. Waste Manag 34:238–241

Song LY, Shi L, Zhao Y, Li H (2011) Novel engineering controls to increase leachate contaminant degradation by refuse: from lab test to in situ engineering application. Ecol Eng 37:1014–1919

Spagni A, Marsilli-Libelli S (2009) Nitrogen removal via nitrite in a sequencing batch reactor treating sanitary landfill leachate. Bioresour Technol 100:609–614

Sponza DT, Agdag ON (2004) Impact of leachate recirculation and recirculation volume on stabilization of municipal solid wastes in simulated anaerobic bioreactors. Process Biochem 39:2157–2165

Sun J, Li X, Feng J, Tian X (2009) Oxone/Co^{2+} oxidation as an advanced oxidation process: comparison with traditional Fenton oxidation for treatment of landfill leachate. Water Res 43:4363–4369

Sun Y, Sun X, Zhao Y (2011) Composition of semi-aerobic and anaerobic degradation of refuse with recirculation after leachate treatment by aged refuse bioreactor. Waste Manag 31:1202–1209

USEPA (1997) Landfill reclamation. USEPA530-F-97-001

US EPA (2010) Municipal solid waste generation, recycling and disposal in United States: facts and figures for 2009. EPA-530-F-010-012, Washington, DC

UN-HABITAT (2010) Collection of Municipal Solid Waste in Developing Countries. United Nations Human Settlements Programme (UN-HABITAT), Nairobi

Varank G, Demir A, Top S, Sekman E, Akkaya E, Yetilmezsoy K, Bilgili MS (2011) Migration behavior of landfill leachate contaminants through alternative composite liners. Sci Total Environ 409:3183–3196

Vrhovac VG, Orescanian V, Gajski G, Geric M, Ruk D, Kollar R, Brkanac SR, Cvjetko P (2013) Toxicological characterization of the landfill leachate prior/after chemical and electrochemical treatment: a study on human and plant cells. Chemosphere 93:939–945

Walender U, Henryson T, Welander T (1997) Nitrification of landfill leachate using suspended carrier biofilm technology. Water Res 31:2351–1355

Wang F, Smith DW, El-Din GM (2003) Application of advanced oxidation method for landfill leachate treatment—a review. J Environ Eng Sci 2:413–427

Wang F, Sun Y, Zhou R (2012) Experimental study on the treatment of chromium-containing wastewater by aged refuse. Prosedia Environ Sci 16:598–605

Wang C, Xie B, Han L, Xu X (2013) Study of anaerobic ammonium oxidation bacterial community in the aged refuse bioreactor with 16S rRNA gene library technique. Bioresour Technol 145:65–70

Wang C, Zhao Y, Xie B, Peng Q, Hassan M, Wang X (2014) Nitrogen removal pathway of anaerobic ammonium oxidation in on-site aged refuse bioreactor. Bioresour Technol 159:266–271

Wang QH, Hang LH, Tian SL, Sun PTC, Xie WM (2007) A pilot-study on treatment of a waste gas containing butyle acetate, *n*-butyle alcohol and phenylacetic acid from pharmaceutical factory by bio-trickling filter. Biochem Eng J 37:42–48

Wang ZW, Wu ZC, Tang SJ (2009) Extracellular polymeric substances (EPS) properties and their effects on membrane fouling in a submerged membrane bioreactor. Water Res 43:2504–2512

Wiszniowski J, Robert D, Surmacz–Gorska J, Miksch K, Weber JV (2006) Landfill leachate treatment methods: a review. Environ Chem Letters 4:51–61

World Bank (2012) What a waste: a global review of solid waste management. Daniel, H and Perinaz, BT (eds) 1818 H Street, NW-Washington, DC 20433 USA www.worldbank.org/urban

Xie B, Lv Z, Lv BY, Gu YX (2010) Treatment of mature landfill leachate by biofilters and Fenton oxidation. Waste Manage 30:2108–2112

Xie B, Xiong S, Liang S, Hu C, Zhang X, Lu J (2012) Performance and bacterial composition of aged refuse reactors treating mature landfill leachate. Bioresour Technol 103:71–77

Xie B, Lv Z, Hu C, Yang X, Li X (2013) Nitrogen removal through different pathways in an aged refuse bioreactor treating mature landfill leachate. Appl Microbiol Biotechnol 97:9225–9234

Yan J, Hu YY (2009) Comparison of partial nitrification to nitrite for ammonium rich organic waste water in sequencing batch reactors and continuous stirred tank reactor at laboratory scale. Water Sci Technol 60:2861–2868

Yang ZQ, Zhou SQ (2008) The biological treatment of landfill leachate using a simultaneous aerobic and anaerobic (SAA) bioreactor system. Chemosphere 72:1751–1756

Zhang QQ, Tian BH, Abbas G, Fang CR, He R (2013) Investigation on characteristics of leachate and concentrated leachate in three landfill leachate treatment plants. Waste Manag 33:2277–2286

Zhao Y, Shao F (2004) Use of an aged-refuse biofilter for the treatment of feedlot wastewaters. Environ Eng Sci 21(3):349–360

Zhao Y, Li H, Wu J, Gu G (2002) Treatment of leachate by aged-refuse-based biofilter. J Environ Eng ASCE 128:662–668

Zhao Y, Chao X, Niu D (2006) The basic characteristics of aged refuse. J Tongji University 34:1360–1364 (In Chinese with English Abstract)

Zhao Y, Lou Z, Guo Y, Xu D (2007) Treatment of sewage using an aged-refuse-based bioreactor. J Environ Manag 82:32–38

Zhao R, Novak JT, Goldsmith CD (2012) Evaluation of onsite biological treatment for landfill leachates and its impact: a size distribution study. Water Res 46:3837–3848