

# Applicability of anaerobic membrane bioreactors for landfill leachate treatment: Review and opportunity

Salahaldin M A Abuabdou, Mohammed J K Bashir, Ng Choon Aun, Sumathi Sethupathi

Department of Environmental Engineering, Faculty of Engineering and Green Technology (FEGT), Universiti Tunku Abdul Rahman, 31900 Kampar, Perak, Malaysia

E-mail: jkbashir@utar.edu.my

**Abstract.** Sanitary landfilling is nowadays the most common way to eliminate municipal solid wastes (MSW). The resulted landfill leachate is a highly contaminated liquid. Even small quantities of this high-strength leachate can cause serious damage to surface and ground water receptors. Thus, these leachates must be appropriately treated before being discharged into the environment. In the last years, anaerobic membrane bioreactor (AnMBR) technology is being considered as a very attractive alternative for leachate treatment due to the significant advantages. In the last decade, many studies have been conducted in which various types of anaerobic reactors were used in combination with membranes. This paper is a review of the potential of anaerobic membrane bioreactor technology for municipal landfill leachate treatment. A critical review in AnMBR performance interesting landfill leachate in lab scale is also done. In addition, the review discusses the impact of the various factors on both biological and filtration performances of anaerobic membrane bioreactors.

## 1. Introduction

Since humans began to build communities within a concentrated area, waste management has become an issue of concern. The sanitary landfill method for the ultimate disposal of solid waste material continues to be widely accepted and used due to its economic advantages. Leachate may carry insoluble liquids (such as oils) and small particles in the form of suspended solids. Bashir *et al* [1] and Aziz *et al* [2] reported that the generation of highly contaminated leachate can seep into the ground and contaminate the groundwater, surface water, and soil. Thus, the generated leachate must be appropriately treated before being discharged into the environment. Leachate characteristics may change from time to time and site to site owing to the parameters such as moisture content, waste composition, temperature, climatic changes etc. [3]. Based on the characteristics of leachate and the literature review concerning leachate treatment, various processes can be used to treat landfill leachate. Membrane bioreactors have been widely applied at full scale on industrial wastewater treatment and some plants have been adapted to leachate treatment [4]. Anaerobic digestion is one of the most important processes used for various industrial wastewaters as well as sewage treatments because it combines pollution reduction and energy production. An AnMBR can be simply defined as a biological treatment process operated without oxygen and using a membrane to provide solid–liquid separation [5]. The objective of this article is to review and evaluate the effectiveness of the AnMBR in landfill leachate treatment with inclusive of



limitations and future perspectives. This overview is based on published reports and journal papers that represent landfills and different treatment methods.

### *1.1 Landfill leachate (LFL) characteristics & Treatment*

The excess rainwater percolating through the waste layers in a landfill generates highly contaminated leachate. The leachate is a mixture of high concentration organic and inorganic contaminants and need to be treated due to their toxicity or bad environmental impact [6]. Landfill leachate may contain pollutants that can be categorized into four groups (dissolved organic matter, inorganic macro components, heavy metals, and xenobiotic organic compounds). There are three types of landfill leachate based on its age, which can be classified as young leachate (acid-phase, <5years), intermediate leachate (5–10years), old or stabilized leachate (methanogenic-phase, >10years) [4,7]. Leachate composition varies significantly among landfills according to waste composition, waste age, and landfilling technology. Buried of refuse in landfills over many years in a series of cells and lifts, will result on different parts of the landfill to be in different phases of decomposition. In the long methanogenic phase, a more stable leachate, with lower concentrations and a low BOD/COD-ratio, was observed [8].

Risk assessment of landfill leachate is traditionally related to chemical analyses of specific compounds present in the leachate. The removal of organic material based on chemical oxygen demand (COD), biological oxygen demand (BOD) and ammonium from leachate is the usual prerequisite before discharging the leachates into natural waters [4]. As landfilling solid waste is an anaerobic process, it produces landfill gases that consist of CO<sub>2</sub>, CH<sub>4</sub>, H<sub>2</sub>S, NH<sub>3</sub> and other traces of gas, it can be harvested, treated and applied for electricity generation or direct heating if not being flared [9]. The knowledge of leachate quality is particularly significant in choosing an appropriate treatment technique. The technologies which were developed for the treatment of landfill leachate could be classified as physical, chemical, and biological [3]. Based on evolution, landfill leachate treatment process may depend on conventional, new technique or a combination of both. Conventional landfill leachate treatment techniques can be classified into three major groups: (a) leachate transfer: recycling and combined treatment with domestic sewage, (b) biodegradation: aerobic and anaerobic processes and (c) chemical and physical methods: chemical oxidation, adsorption, chemical precipitation, coagulation/flocculation, sedimentation/flotation and air stripping [4]. To select adequate treatment process which could eliminate contaminants from the leachates, different physicochemical and biological methods or their various combinations could be carried out: (i) biological to remove biodegradable materials, where the control relationships parameters such as cell residence time (sludge age), food-microorganism ratio (F/M), hydraulic retention time (HRT), sludge retention time (SRT), etc. allow to assess operating conditions of biological system (ii) ion exchange to remove ammonia and organic compound, (iii) coagulation–flocculation to remove colloids and metals, (iv) adsorption via activated carbon (AC) to remove organics and metals, and (v) advanced oxidation process (AOPs) to remove organic compounds [10]. The main membrane processes applied in landfill leachates treatment are microfiltration, ultrafiltration, nanofiltration and reverse osmosis. Which consider as the new techniques [4]. In fact, membrane technology is widely implemented and has excellent filtering capability in removing all suspended, colloidal solids and bacteria including attached viruses or adsorbed compounds [11].

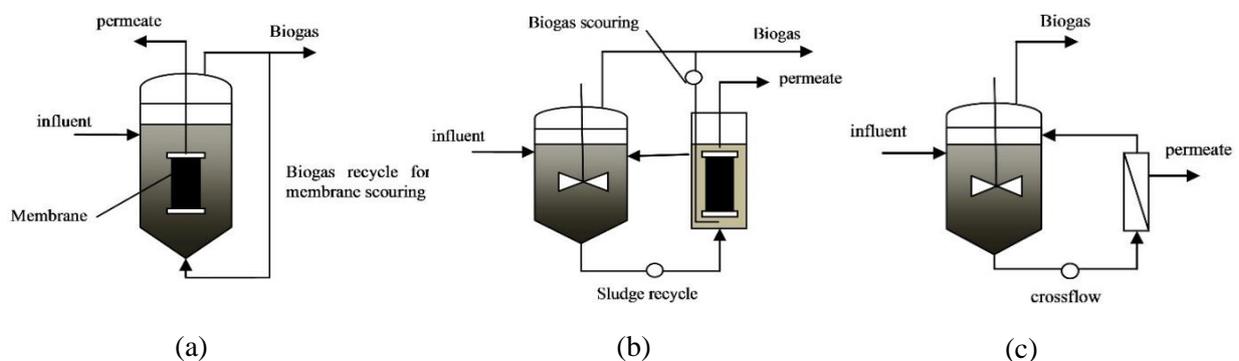
### *1.2 Aerobic and anaerobic membrane reactors*

It is well-known that biologically treated landfill leachate often fails to fulfill the regulatory discharge standards [12], while the final performance of the activated sludge (AS) process depends mostly on good solid liquid separation between treated water and sludge in the final clarifier. The adsorption process is used as a stage of integrated chemical–physical–biological process for landfill leachate treatment. The most frequently used adsorbent is granular or powdered activated carbon due to its high capability to remove organic compounds from wastewater [1]. Carbon adsorption permits 50–70% removal of both COD and ammonia nitrogen [10]. The use of membranes in aerobic biological wastewater treatment processes has been well established over the past 15 years [5]. An MBR system provides various

advantages such as (i) minimised excess sludge production, (ii) high rate of organic matter removal, (iii) reduced aeration cost for energy saving, (iv) smaller footprint, and (v) generation of superior effluent quality to achieve a more economical wastewater treatment system [12]. Fouling or biofouling is one of the major disadvantages of these membrane processes, which induced by deposits of inorganic, organic and microbiological substances on both the membrane surface and inside the membrane pores. According to Khanal [13], aerobic systems have a small startup time (1 or 2 weeks) compared to anaerobic, which can take several months and even longer if the reactor operates with low temperature conditions. The net biomass production for the anaerobic treatment is low (up to ten times less than that of aerobic treatment). In addition, the biogas recovery represents one of the major advantages of AnMBR. A high rate treatment efficiency can be reached using both of aerobic and anaerobic system combined with membranes with different stages to take benefits of all of them.

## 2. AnMBR performance

Current researches demonstrated that the AnMBR technology can be used for the treatment of many types of wastewaters with a great potential to recover energy and resources from high strength wastewaters. Simply defined, an AnMBR is an anaerobic bioreactor coupled with membrane filtration. The membrane filtration component can exist in three configurations: internal submerged, external submerged, or external cross-flow as presented in figure 1. In an external cross-flow configuration, the membrane unit is separate from the bioreactor and the membranes operate under pressure to produce permeate. A significant advantage of the anaerobic process is the biogas recovery. Lin *et al* [5] stated that continuous biogas production could be observed in AnMBR systems for various wastewaters treatment. The observed methane yield ranged 0.23–0.33 LCH<sub>4</sub>/g COD removal has been reported [14]. The methane rich biogas can be used for digester heating, electricity generation or even recycled for fuel production. AnMBR consists of the main totally closed basin connected to the influent, biogas, re feeding and outlet pipes when the membrane is submerged on the reactor, and with extra cross flow pipe in case of external membranes.



**Figure 1.** Different AnMBR system configurations: (a) Submerged membrane AnMBR; (b) AnMBR with external submerged hollow fiber membrane; (c) AnMBR with external crossflow membrane [15].

### 2.1. AnMBR performance for leachate treatment

Anaerobic membrane bioreactor (AnMBR), which combines anaerobic process and membrane technology, is attracting noticeable interest in both research community and industrial sectors [5]. It can be seen from table 1 which summarizes AnMBR applications in landfill leachate treatment (Lab scale), the applied temperature ranged at 34–37°C, which was mesophilic. The digestion process was better at mesophilic (30–45°C) [11], which requiring heating of reactors. It is appeared that the HRT was between 1–10 d, which was rather higher than the values applied in other wastewater types. Trzcinski and Stuckey [16] applied two different values for SRT and HRT in a CSTR with membrane (i.e., 1.5 d HRT with 30 d SRT and 1.1 d HRT with 300 d SRT) which resulted in 79 and 90% COD removal, respectively.

**Table 1.** Performance of AnMBRs in landfill leachate treatment (Lab Scale).

Source WW/ Reference	Scale/ Volume	Reactor type (All are Anaerobic)	initial COD (mg/l)	Membrane configuration	Operational condition			Final COD (mg/l)	Rem.* (%)	Ref.
					Temp. °C	HRT	SRT			
Landfill leachate Thessaloniki (Greece)	Lab (5 L)	Membrane SBR	1391– 3977	Sub (UF/HF)	-	10 d	infinite	600- 2500	40–60	[17]
Landfill leachate Czestochowa (Poland)	Lab (29 L)	Stirred tank	2800– 5000	Sub. (UF/Cap)	-	1–7 d	-	417	70–90	[16]
Sanitary landfill leachate	Lab (44 L)	CSTR + M	-	Ext. (Ceramic tubular membrane) Pore size 0.2 µm	34-36	2.04 d	-	-	90.4	[17]
Landfill leachate Synthetic	Lab (-)	UASB	16,000– 22,000	Ext. (UF/flat sheet)	-	4.16 d	-	6400- 13200	40–60	[18]
Municipal solid waste	Lab (3 L)	CSTR + M	4000- 26000	Sub. (Kubota PE flat sheet) Pore size 0.4 µm	35±1	1.6- 2.3 d	-	400- 600	> 90	[19]
Landfill leachate Jebel Chakir (Tunisia)	Lab (50 L)	Jet flow bioreactor	14,870– 41,000	Ext. (UF)	37	7 d	-	1170- 3770	89–92	[20]
Municipal solid waste leachate,	Lab (3 L)	CSTR + M	-	Sub. (PE flat sheet membrane) Pore size 0.4 µm	35	1.5 d	30 d	1000	79-95	[16]
Municipal solid waste leachate,	Lab (3 L)	CSTR + M	-	Sub. (PE flat sheet Pore size 0.4 µm	35	1.1 d	300 d	-	90	[16]

WW: Wastewater; COD: Chemical Oxygen Demand; Temp.: Temperature; HRT: Hydraulic Retention Time; SRT: Sludge Retention Time; Ref.: Reference; Ex.: External; UF: Ultrafiltration; Sub.: Submerged; CSTR+M: Completely Stirred Tank Reactor + Membrane; UASB: Up flow Anaerobic Sludge Blanket; PE: polyethylene.

\* Rem.: COD Removal Efficiency.

### 3. Factors affecting the AnMBR process performance

The AnMBR process performance is affected by the efficiency of both biological treatment and filtration process, which influenced by the operational condition, biomass and membrane characteristics.

#### 3.1. Factors affecting the treatment performance

In general, AnMBR operation with relatively long HRTs and SRTs was favorable, to enhance methane recovery, treatment performance and reduce sludge production [18]. Although startup could be achievable relatively fast in mesophilic conditions, periods of 2 to 4 months are quite common [13]. Table 2 presents the operational parameters effects on treatment efficiency and highlight on its optimum values. For some parameters, like temperature there is no recommendation observed from previous studies focused on its effects on the anaerobic treatment for landfill leachate treatment, but it is presented here from other wastewater types as indicator for orientation purposes.

#### 3.2. Factors affecting the membrane performance

MBR system is one of the promising methods which involve the combination of biological treatment with the aids of activated sludge coupling with a direct solid-liquid separation by membrane filtration [11]. One of the major contributors to the operating cost and maintenance of membranes, is the membrane fouling [19]. The major factors affecting fouling are biochemical kinetic parameters, temperature, membrane characteristics, mixed liquor characteristics, operational style and reactor hydraulic conditions. Therefore, membrane fouling mechanisms are very complicated due to the

complex rheological and physiological characteristics of mixed liquors [11]. It seems obviously from table 3, that fouling parameters have a strong impact on the membrane performance.

**Table 2.** Operational parameters effects on efficiency of landfill leachate treatment using AnMBRs

Operational conditions	Description of the effects on AnMBR efficiency (with the optimization values)	Wastewater type	Reference
HRT	Long HRT are required to have high efficiency (1.5 d < HRT < 11.8 d)	Landfill leachate	[5]
OLR	High OLR results High efficiency, and the COD removal gradually improved with cont. operation (OLR > 2.5 kg COD/m <sup>3</sup> /d)	Landfill leachate	[5]
SRT	Long SRT yields to high efficiency (20 < SRT < 70.5 d)	Landfill leachate	[20]
Start-up period	(SUP > 90 days)	Landfill leachate	[21]
pH	AnMBR systems operate at near neutral pH since anaerobic digestion takes place within pH 6.5–8.5 (7.0 < pH < 8.0)	Municipal wastewater	[22]
BOD/COD ratio	-For young leachate, the efficiency decreased with decreasing BOD/COD ratio, then (BOD/COD > 0.40) -For old leachate, the BOD/COD ratio becomes less visible, when (BOD/COD ≤ 0.2)	Landfill leachate	[23]
Temperature	-Higher temperatures are known to improve methanogenesis -A deterioration of membrane flux always occurred due to sludge deflocculation and EPS released caused by high temperature. -(COD removal efficiencies close to 90% were achieved at both 35° C and 20° C) -Temperature displayed no significant effect on the biogas yield.	Municipal wastewater swine waste	[24] [25]

**Table 3.** Description of the effects of fouling parameters on membrane fouling in AnMBRs.

Fouling parameters	Description of the effects on membrane fouling	Ref.
<b>Operational conditions</b>		
HRT	A decrease in HRT resulted in a decrease in solids removal efficiency	[26]
OLR	Filtration resistance increases with organic loading	[27]
SRT	The relationship between SRT and membrane fouling is complex, and highly depends on the applied HRT and the feed characteristics. Infinite SRT probably lowered specific biomass activity due to accumulation of inert particulate matter in the MBR	[28] [23]
Permeate flux	Permeate flux increased → fouling rate increased	[5]
Temperature	Temperature increased → COD <sub>sup</sub> increased → stable flux decreased The fouling rate is reduced with the temperature increasing	[16] [24]
pH	the fouling at pH 6.5 and 7.5 were quite similar and less severe than that at pH 5.5 and 8.5. (6.5 < pH < 7.5)	[29]
<b>Biomass Characteristics</b>		
MLSS	(Higher than Aerobic MBR) MLSS is positively correlated to membrane fouling	[5]
PSD	Flocs size significantly affected cake formation, filtration resistance	[30]

	(500% higher than the aerobic MBR)	[31]
SMP	High SMP content results in serious membrane fouling	
EPS	More EPS is negatively impact membrane fouling	[32]
<b>Membrane characteristics</b>		
Pore size	Pore size increased → attainable flux decreased	[5]
General	Fouling of PEI membrane was faster than. High shear conditions have also been reported as detrimental for anaerobic biomass activity. The efficient trans-membrane pressure varied from 1 to 2 bar	[33] [5]
		[34]

---

COD<sub>sup</sub>: Soluble COD; MLSS: Mixed liquor suspended solids; MBR: Membrane bioreactor; PSD: Particle size distribution; SMP: soluble microbial products; EPS: extracellular polymeric substances; PEI: Polyethylene.

#### 4. AnMBR limitations and future perspectives

If AnMBR started at low temperature, conditions will be worse, reduction of biomass growth will happen and requiring longer SRT to stabilize [19]. In this way, operating without external heating is an attractive proposal for broadening anaerobic digestion applications, now limited to warm climate locations [35]. In addition, McKeown *et al* [25] suggested the use of pre-acclimated inoculum biomass to reduce start-up times, because the biomass will already be adapted to the new temperature conditions. As with the general sewage leachate water quality is quite different, it should strengthen the pre-or post-processing technology. As well, explore technically and economically feasible process plan, process combination will be a branch in the various processes and coordination problems with research. These aspects like: evaluation of both technical and economic feasibility of MBRs, submerged MBRs, treating leachate at the full-scale level, determination of optimum operating conditions with well controlled pilot studies.

#### 5. Conclusion

AnMBR technology features many advantages over aerobic treatment and conventional anaerobic methods, and the developments in membrane materials and modules added to its advantages. There are many factors affect the efficiency of the AnMBR in both of biodegradation and filtration process. Despite the rapid development of AnMBRs, there are remaining several barriers or challenges that limit their widespread practical application for landfill leachate treatment. Thus, combination of membranes with different types of anaerobic high-rate reactor configurations for landfill leachate treatment should be further investigated. On the other hand, performing a proper and robust start-up of AnMBR in ambient temperatures and membrane fouling are still challenging. This article presented a comprehensive review on AnMBR performance treating landfill leachate.

#### Acknowledgment

The authors would like to express their gratitude for the Universiti Tunku Abdul Rahman (UTAR). This study was made possible through the financial support provided under UTARRF- 6200/M19.

#### References

- [1] Bashir M J K, Aziz H A, Amr S S A, Sethupathi, S a p, Ng C A and Lim J W 2015 The competency of various applied strategies in treating tropical municipal landfill leachate *Desalination and Water Treatment* **54** 2382
- [2] Aziz S Q, Aziz H A, Bashir M J K and Mojiri A 2015 Assessment of various tropical municipal landfill leachate characteristics and treatment opportunities *Global NEST J.* **17** 439
- [3] Abdelaal F B, Rowe R K and Islam M Z 2014 Geotextiles and Geomembranes Effect of leachate composition on the long-term performance of a HDPE geomembrane *Geotext. Geomembranes* **XXX** 1
- [4] Renou S, Givaudan J G, Poulain S, Dirassouyan F and Moulin P 2008 Landfill leachate

- treatment : Review and opportunity *J. of Hazardous Materials* **150** 468
- [5] Lin H, Peng W, Zhang M, Chen J, Hong H and Zhang Y 2013 A review on anaerobic membrane bioreactors: Applications , membrane fouling and future perspectives *DES* **314** 169
- [6] Wiszniowski J, Robert D, Surmacz-Gorska J, Miksch K and Weber J V 2006 Landfill leachate treatment methods : A review *Environ Chem Lett* **4** 51
- [7] Foo K Y and Hameed B H 2009 An overview of landfill leachate treatment via activated carbon adsorption process *J. Hazard. Mater.* **171** 54
- [8] Kjeldsen P, Barlaz M A, Rooker A P, Baun A, Ledin A and Christensen T H 2002 Present and long-term composition of MSW landfill leachate: A review *Crit. Rev. Environ. Sci. Technol.* **32** 297
- [9] Chua K H, Jati E, Sahid M and Leong Y P 2005 Sustainable Municipal Solid Waste Management and GHG Abatement in Malaysia *ST-4: Green & Energy Management* 1.
- [10] Salem Z, Hamouri K, Djemaa R and Allia K 2008 Evaluation of landfill leachate pollution and treatment *Desalination* **220** 108
- [11] Tan S P, Kong H F, Bashir M J K, Lo P K, Ho C and Ng C A 2017 Treatment of Palm Oil Mill Effluent Using Combination System of Microbial Fuel Cell and Anaerobic Membrane Bioreactor *Bioresour. Technol.* **245** 916
- [12] Ng C A, Wong L Y, Chai H Y, Bashir M J K, Ho C D, Nisar H and Lo P K, 2017 Investigation on the performance of hybrid anaerobic membrane bioreactors for fouling control and biogas production in palm oil mill effluent treatment *Water Science & Technology* **76** 1389
- [13] Khanal S K 2011 *biotechnology for bioenergy production: principles and applications* (John Wiley Anaerobic & Sons)
- [14] Lin H, Chen J, Wang F, Ding L and Hong H 2011 Feasibility evaluation of submerged anaerobic membrane bioreactor for municipal secondary wastewater treatment *Desalination* **280** 120
- [15] Chang S 2014 Anaerobic Membrane Bioreactors (AnMBR) for Wastewater Treatment *Advances in Chemical Engineering and Science* **4** 56
- [16] Trzcinski A P and Stuckey D C 2010 Treatment of municipal solid waste leachate using a submerged anaerobic membrane bioreactor at mesophilic and psychrophilic temperatures : Analysis of recalcitrants in the permeate using GC-MS *Water Res.* **44** 671
- [17] Tsiologorgis J, Zouboulis A, Samaras P and Zamboulis D 2008 Application of a membrane sequencing batch reactor for landfill leachate treatment *Desalination* **221** 483
- [18] Ho J and Sung S 2009 Anaerobic membrane bioreactor treatment of synthetic municipal wastewater at ambient temperature *Water Environ. Res.* **81** 922
- [19] Smith A L, Stadler L B, Love N G, Skerlos S J and Raskin L 2012 Perspectives on anaerobic membrane bioreactor treatment of domestic wastewater: a critical review *Bioresour. Technol.* **122** 149
- [20] Trzcinski A P and Stuckey D C 2009 Continuous treatment of the organic fraction of municipal solid waste in an anaerobic two-stage membrane process with liquid recycle *Water Res.* **43** 2449
- [21] Xie Z, Wang Z, Wang Q, Zhu C and Wu Z 2014 Bioresource Technology An anaerobic dynamic membrane bioreactor ( AnDMBR ) for landfill leachate treatment: Performance and microbial community identification *Bioresour. Technol.* **161** 29
- [22] Weiland P 2010 Biogas production: current state and perspectives *Appl. Microbiol. Biotechnol.* **85** 849
- [23] Ahmed F N and Lan C Q 2012 Treatment of landfill leachate using membrane bioreactors : A review *DES* **287** 41
- [24] Ozgun H, Kaan R, Evren M, Kinaci C, Spanjers H and Van Lier J B 2013 A review of anaerobic membrane bioreactors for municipal wastewater treatment : Integration options, limitations and expectations *Sep. Purif. Technol.* **118** 89
- [25] Ndegwa P M 2008 Effects of cycle-frequency and temperature on the performance of

- anaerobic sequencing batch reactors (ASBRs) treating swine waste *Bioresource Technology* **99** 1972
- [26] An Y, Yang F, Buccioli B and Wong F 2009 Municipal wastewater treatment using a UASB coupled with cross-flow membrane filtration *J. Environ. Eng.* **135** 86
- [27] Trussell R S, Merlo R P, Hermanowicz S W and Jenkins D 2006 The effect of organic loading on process performance and membrane fouling in a submerged membrane bioreactor treating municipal wastewater *Water Res.* **40** 2675
- [28] Baek S H, Pagilla K R and Kim H-J 2010 Lab-scale study of an anaerobic membrane bioreactor (AnMBR) for dilute municipal wastewater treatment *Biotechnol. Bioprocess Eng.*, **15** 704
- [29] Sanguanpak S, Chiemchaisri C, Chiemchaisri W and Yamamoto K 2015 International Biodeterioration & Biodegradation Influence of operating pH on biodegradation performance and fouling propensity in membrane bioreactors for landfill leachate treatment *Int. Biodeterior. Biodegradation* **102** 64
- [30] Lin H J, Gao W J, Leung K T and Liao B Q 2011 Characteristics of different fractions of microbial flocs and their role in membrane fouling *Water Sci. Technol.* **63** 262
- [31] Martin-Garcia I 2011 Impact of membrane configuration on fouling in anaerobic membrane bioreactors *J. Memb. Sci.* **382** 41
- [32] Jeison D, Telkamp P and Van Lier J B 2009 Thermophilic sidestream anaerobic membrane bioreactors: the shear rate dilemma *Water Environ. Res.* **81** 2372
- [33] Gao D-W, Zhang T, Tang C.-Y. Y, Wu W.-M, Wong C.-Y., Lee Y H, Yeh D H and Criddle C S 2010 Membrane fouling in an anaerobic membrane bioreactor: differences in relative abundance of bacterial species in the membrane foulant layer and in suspension *J. Memb. Sci.* **364** 331
- [34] Zayen A 2006 Anaerobic membrane bioreactor for the treatment of leachates from Jebel Chakir discharge in Tunisia *J. Hazard. Mater.* **177** 918
- [35] Liao B-Q, Kraemer J T and Bagley D M 2006 Anaerobic membrane bioreactors: applications and research directions *Crit. Rev. Environ. Sci. Technol.* **36** 489