Treatment of landfill leachate in municipal wastewater treatment plants and impacts on effluent ammonium concentrations.

Title	Treatment of landfill leachate in municipal wastewater treatment plants and impacts on effluent ammonium concentrations.
Author(s)	Brennan, Raymond B.;Clifford, Eoghan;Devroedt, E.;Morrison, Liam;Healy, Mark G.
Publication Date	2016-12-05
Publisher	Elsevier

Published as: Brennan, R.B., Clifford, E., Devroedt, C., Morrison, L., Healy, M.G. 2017. Treatment of landfill leachate in municipal wastewater treatment plants and impacts on effluent ammonium concentrations. Journal of Environmental Management 188: 64 – 72. http://dx.doi.org/10.1016/j.jenvman.2016.11.055

Treatment of landfill leachate in municipal wastewater treatment plants and impacts on effluent ammonium concentrations

R.B. Brennan*[1,2], E. Clifford[1,2], C. Devroedt[1,3], L. Morrison[2,4], M.G. Healy[1,2]

[1]Civil Engineering, National University of Ireland, Galway, Ireland.

[2]Ryan Institute, National University of Ireland, Galway, Ireland.

[3]Institut National des Sciences Appliquées de Lyon, Lyon, France.

[4]Earth and Ocean Sciences, School of Natural Sciences, National University of Ireland, Galway, Ireland.

*Corresponding author. Room 1-029, New Engineering Building, NUI Galway, Galway, Ireland; E-mail address: raymond.brennan@nuigalway.ie

Abstract

Landfill leachate is the result of water percolating through waste deposits that have undergone aerobic and anaerobic microbial decomposition. In recent years, increasingly stringent wastewater discharge requirements have raised questions regarding the efficacy of co-treatment of leachate in municipal wastewater treatment plants (WWTPs). This study aimed to (1) examine the co-treatment of leachate with a 5-day biochemical oxygen demand (BOD_5): chemical oxygen demand (COD) ratio less than or slightly greater than 0.26 (intermediate age leachate) in municipal WWTPs (2) quantify the maximum hydraulic and

mass (expressed as mass nitrogen or COD) loading of landfill leachate (as a percentage of the total influent loading rate) above which the performance of a WWTP may be inhibited, and (3) quantify the impact of a range of hydraulic loading rates (HLRs) of young and intermediate age leachate, loaded on a volumetric basis at 0 (study control), 2, 4 and 10% (volume landfill leachate influent as a percentage of influent municipal wastewater), on the effluent ammonium concentrations. The leachate loading regimes examined were found to be appropriate for effective treatment of intermediate age landfill leachate in the WWTPs examined, but co-treatment may not be suitable in WWTPs with low ammonium-nitrogen (NH_4-N) and total nitrogen (TN) emission limit values (ELVs). In addition, intermediate leachate, loaded at volumetric rates of up to 4% or 50% of total WWTP NH_4-N loading, did not significantly inhibit the nitrification processes, while young leachate, loaded at volumetric rates greater of than 2% (equivalent to 90% of total WWTP NH_4-N loading), resulted in a significant decrease in nitrification. The results show that current hydraulic loading-based acceptance criteria recommendations should be considered in the context of leachate NH_4-N composition. The results also indicate that co-treatment of old leachate in municipal WWTPs may represent the most sustainable solution for ongoing leachate treatment in the cases examined.

Keywords: landfill leachate co-treatment; ammonium; activated sludge, nitrification inhibition; municipal solid waste.

Introduction

Landfill leachate is the result of water percolating through waste deposits that have undergone aerobic and anaerobic microbial decomposition (Chofqi et al., 2004; Gupta et al., 2014; Mukherjee et al., 2014). Its composition is a function of the type of waste in the landfill, landfill age, climate conditions, and hydrogeology of the landfill site (Chofqi et al., 2004; Slack et al., 2005). A landfill site will produce leachate throughout its working life and also for several hundred years after it is decommissioned (Wang, 2013). The control of a landfill site, and appropriate treatment of the leachate it produces, is paramount in the protection of the surrounding environment, as leachate contamination of groundwater, rivers, lakes and soils has the potential to negatively affect local habitats, resources and human health (Ağdağ and Sponza, 2005; Marshall, 2009).

The European Union (EU) Landfill Council Directive 1999/31/EC (EC, 2001) and subsequent waste management legislation (EC, 2008) have resulted in major changes in the waste management sector in Europe over the last 30 years. The Landfill Directive sets targets that (1) reduce the percentage of waste that can be consigned to landfill for each member state (2) decrease the quantity of biodegradable municipal waste sent to a landfill, and (3) places responsibility on landfill owners to budget for the aftercare of a landfill site for a minimum of 30 years after operation has ceased. Prior to the implementation of this Directive, landfilling across the EU was unregulated and poorly planned (EC, 2007). The Directive has resulted in dramatic improvements in the manner in which landfills, and specifically landfill leachate, is managed (McCarthy et al., 2010; Brennan et al., 2015). While there has been a decline in landfilling in recent years, leachate generation is a legacy problem, and the treatment of leachate is the major management issue facing landfill operators (Zhang et al., 2010; Brennan et al., 2015). Many landfills are not located close to suitable receiving waters (Knox et al., 2015). Therefore, the most sustainable option may be to transfer leachate to wastewater treatment plants (WWTPs) for final treatment.

Leachate contains high levels of 5-day biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), ammonium-nitrogen (NH_4-N), chloride (Cl), sodium (Na), potassium (K), nitrogen (N), boron (B), solvents, phenols, hardness and metals, including iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), cobalt (Co), chromium (Cr), nickel (Ni), cadmium (Cd) and lead (Pb) (Tatsi et al., 2003; Chofqi et al., 2004; Ağdağ and Sponza, 2005; Marzougui and Mammou, 2006). Young leachate (generated in operational landfills or landfills closed for less than five years (Renou et al., 2008)) is highly biodegradable and exhibits COD and NH_4-N concentrations of up to 80,000 and 3,100 mg L^{-1}, respectively, and BOD_5:COD ratios of up to 0.7 (Stegmann et al., 2005). As a result, biological treatment methods are reasonably efficient in the removal of COD, NH_4 and metals (Kurniawan et al., 2006). Conversely, older (stabilised) leachate is less biodegradable and contains methanogenic leachate with BOD_5:COD ratios < 0.2 (Stegmann et al., 2005), and therefore is not as efficiently treated using biological methods. In the current paper, landfills are defined as young (operational/closed less than five years), intermediate (closed more than five year but less than 10), and old (closed more than ten years) (after Renou et al., 2008).

To date, there has been limited work regarding the impacts of co-treatment of landfill leachate and municipal wastewater in WWTPs (Renou et al., 2008), and studies have been largely limited to laboratory-scale batch experiments (Diamadopoulos et al., 1997; Çeçen and Aktaş, 2004; Capodici et al., 2014; Wu et al., 2015; Mojiri et al., 2016). These studies have generally concluded that WWTP removal efficiency is not adversely affected, provided the total hydraulic loading of leachate does not exceed 10% of the total municipal wastewater entering the WWTP. However, at these volumetric loading rates effluent NH_4-N and total nitrogen (TN) may be significantly impacted due to their relatively high concentrations in landfill leachate (Diamadopoulos et al., 1997; Ye et al., 2014; Ferraz et al., 2014). The lack of recent studies examining co-treatment of leachate in operational municipal WWTPs is a concern for WWTP managers, as wastewater effluent is subject to increasingly stringent legislation in the EU. There is a concern that recommendations based on laboratory studies and not site-specific data, may result in failures to achieve compliance.

Studies have demonstrated that co-treatment of young leachate with municipal wastewater does not adversely affect WWTP performance (Diamadopoulos et al., 1997; Kalka, 2012; Ye et al,, 2014); however, the effect of old landfill leachate (BOD_5:COD < 0.01; Renou et al., 2008) has not been widely examined with the exception of Del Borghi et al. (2003), who concluded that old leachate should mixed with young leachate before treatment. The current study (1) examines the co-treatment of leachate with a BOD_5: COD ratio less than or slightly greater than 0.26 (intermediate age leachate) in municipal WWTPs and attempts to quantify the maximum hydraulic and mass (expressed as mass nitrogen or COD) loading of landfill leachate (as a percentage of the total influent loading rate) above which the performance of a WWTP may be inhibited and (2) quantifies the impact of a range of volumetric loading rates (VLRs) of young and intermediate age leachate, loaded on a volumetric basis at 0, 2, 4 and 10% (expressed as volume landfill leachate treated in the WWTP as a percentage of the total influent wastewater to the WWTP), on NH_4-N removal. The study is thus focused on the feeding strategy adoptable in order to minimize the adverse effects of landfill leachate presence in the WWTP.

Materials and Methods

Study sites

Three activated sludge WWTPs, two of which were representative of WWTPs co-treating leachate in Ireland and another which had not received landfill leachate in over one year and hereafter referred to as Sites 1, 2 and 3, were selected for use in this study. Landfill leachate (LL) accepted at Site 1 and 2 (intermediate) and a young landfill leachate from another landfill (young) were identified and hereafter referred to as LL 1, 2 and 3.

WWTP monitoring

Sites 1 and 2 were selected and monitored to determine the impact of leachate loading regime on WWTP performance. Their operational information is given in Table 1. Both WWTPs received leachate (Table 2) at average VLRs, of 1.2 and 2.3% (Table 1). Leachate loading regimes examined during the study were: (1) drip-feed (2) no-leachate addition and (3) shock loading (i.e. relatively large leachate volumes added to the WWTP in a brief pulse). Drip-feed and no-leachate scenarios were examined at Site 1, whereas shock loading was examined at both Site 1 and 2 (Table 3). Refrigerated automatic wastewater samplers (Aqua Cell, UK) were used to collect grab samples at eight-hour intervals at the head of the works prior to primary settlement and at effluent discharge points (effluent wastewater samples) of Sites 1 and 2. Influent and effluent flows were recorded using on-site flow recording equipment. For operational reasons, it was not practical to monitor each loading regime for a time period longer than the sludge age of the WWTP, and this must be taken into account when interpreting differences between leachate loading regimes.

Analysis of wastewater and landfill leachate

Samples were analysed for BOD_5, COD, CODs, filtered total nitrogen (TN_f), filtered total inorganic carbon (TIC_f), filtered total organic carbon (TOC_f), ortho-phosphorus (PO_4-P), nitrate-nitrogen (NO_3-N), nitrite-nitrogen (NO_2-N), alkalinity, sulphate, chloride, NH_4-N and suspended solids (SS). All analyses were conducted in accordance with the standards method for the examination of water and wastewater (APHA et al., 2012). Conductivity and pH were determined using a SAC950 sample changer and a Titralab 870. Total metal concentrations for Cu, Cd, Cr, As, Pb, Hg, and Ni were determined by Inductively Coupled Plasma Mass Spectrometry (ICP-MS) (Agilent 7500a Technologies Inc. USA) following microwave digestion (CEM Discover SPD Microwave Digester) using Trace Metal Grade Nitric Acid (Fisher, UK).

Nitrification inhibition batch experiments

Laboratory batch experiments, conducted to supplement the results of the WWTP study, examined the impact of various landfill leachate on NH_4-N removal in controlled experiments. Landfill leachate LL1 and LL3 were added to a mixed liquor suspended solids (MLSS) samples from Sites 1 and 3 at volumetric loading rates (volume LL/volume MLSS sample) of 0, 2, 4 and 10% (n=3 for each experiment). Landfill leachate and MLSS were collected, transported to the laboratory, and stored at 4°C. Batch experiments were conducted within 12 hours of sample collection. Experiments were conducted in triplicate using 2 L-capacity beakers in a cold room with a controlled temperature of 10°C, which is similar to mean air temperatures observed in Ireland (Met Eireann, 2015). Wastewater/wastewater and leachate mixtures were added to the beakers and immediately following this, aeration commenced using an air-stone placed at the base of each beaker. Beakers were constantly aerated with an air flow sufficient to ensure suspension of solids throughout the experiment. Wastewater/wastewater and leachate mixture pH and dissolved oxygen (DO) were measured and samples withdrawn from the beakers (2 mL) for alkalinity, NH_4-N and NO_3-N analysis at t = 0.125, 0.25, 0.5, 1, 2, 4, 6, 24 and 48 hours. After 48 hours aeration ceased, and filtered and unfiltered samples were taken for analysis for COD and CODs (soluble faction of COD) analysis.

Data analysis

Daily VLR was determined by expressing the daily volume of leachate treated as a percentage of the daily effluent treated at the WWTP. The instantaneous leachate loading rate (VLR_i) was determined by expressing the volume of leachate treated as a percentage of the volume of effluent treated during the time the leachate was discharged to the WWTP/sewer from the tanker or on-site storage tank. Daily leachate BOD_5, COD and NH_4-N mass loads were also expressed as a percentage of daily WWTP influent BOD_5, COD and NH_4-N mass loads. Data were analysed using ANOVA in SPSS (IBM SPSS Statistics 20 Core System, Version 20). Beaker experimental data satisfied the normality assumption, while logarithmic transformations were required for the site monitoring data to satisfy the normality assumption, based on checking post-analysis residuals for normality and homogeneity of variance.

Results

Landfill leachate characterisation

The range and mean concentrations of pH, conductivity, NH_4-N, TN, BOD_5, COD, BOD_5:COD ratio, alkalinity, chloride, sulphate and SS in landfill leachate accepted at the two study sites are shown in Table 2. Concentrations of inhibiting compounds such as NH_4-N (Table 2), As and Cu (Table 4) were not above typical inhibitory thresholds (480 mg L^{-1}, 0.05-0.1 mg L^{-1} and 0.1-0.35 mg L^{-1}, respectively) for nitrifying populations in inactivated sludge (Gerardi, 2002; Henze et al., 2002).

WWTP monitoring

Site 1

Influent volume, COD, BOD_5, TIC_f, TOC_f, TN_f and NH_4-N daily mass loads and concentrations did not significantly differ between the three loading regimes (drip-feed, no leachate and shock loading; $p<0.05$) (Table 3). There were no significant difference between influent and effluent As, Cd, Cr, Cu, Pb, Hg, and Ni concentrations (Table 4). Daily carbon loading rates were similar to VLR (Figure 1), with average daily leachate loading accounting for less than 0.1% and 2% of total BOD_5 and COD loads to the WWTP throughout the study, while average daily TN and NH_4-N loading accounted for a maximum of 9% and 8% of TN and NH_4-N daily loads to the WWTP, respectively. The VLR_i was unchanged during the drip-flow phase, but increased to 16% during the shock loading phase (Figure 1) while instantaneous TN and NH_4-N loading increased to 40% and 39%, respectively. The leachate loading regime at Site 1 did not have a statistically significant impact ($p<0.05$) on percentage removals of BOD_5, COD, TIC_f, TOC_f, TN_f, or NH_4-N (Table 3) or effluent concentrations

(Figure 2) when comparison was made between effluent from drip-feed, no-leachate and shock loading regimes.

Site 2

Influent volume, COD, BOD_5, TIC_f, TOC_f, TN_f and NH_4-N mass loads and concentrations did not significantly differ between high and low shock loading regimes (p<0.05) (Table 3). There were no significant difference between influent and effluent As, Cd, Cr, Cu, and Ni concentrations, but there were significant differences in influent and effluent Pb and Hg (Table 4). The VLR decreased from 2.5 to 0.3% when the loading regime was changed from high to low leachate loading regime, while the equivalent daily BOD_5 loading ratios decreased from 5% to 0.7%, COD from 5.3% to 0.8%, and NH_4-N from 16% to 1.1%. The VLR_i decreased from 15.2 to 1.9% during the high and low leachate loading phases (Figure 1). The leachate loading regime at Site 2 did not significantly impact the COD and BOD_5 removals when comparison was made between the effluent from each leachate loading regime (Table 3). However, TIC_f (p<0.05), TOC_f (p<0.05) and NH_4-N (p<0.001) removals increased significantly when the leachate loading regime was reduced from a high to a low loading rate. Decreasing leachate loading resulted in decreased effluent NH_4-N concentrations, with mean NH_4-N concentrations decreasing from 4.0 mg L^{-1} during the high loading period to 0.65 mg L^{-1} during the low loading period (p<0.001) (Figure 2).

Laboratory batch experiments

Initial COD_f, COD_t, NH_4-N, total oxidised nitrogen (TON), alkalinity, MSLL and VSS concentrations for leachate used in laboratory batch experiments are shown in Table 5.

Addition of intermediate and young leachate to MLSS increased initial NH_4-N and alkalinity concentrations (t=0.125 hr) compared to the control (Figure 3) for Site 1 wastewater and Site 3 wastewater. These increases were statistically significant for the young leachate, but not for the intermediate age leachate ($p<0.05$). Ammonium and alkalinity concentrations were observed to decrease relatively steadily until approximately 6 hr after the experiment started (Figure 3). Following this, a plateau effect was observed, with little further decrease in NH_4-N and alkalinity concentrations with time. However, young leachate, added at a volumetric loading ratio of 4% or above, significantly increased NH_4-N concentrations compared to the control ($p<0.05$). Table 6 shows wastewater/wastewater and leachate mixture pH and DO at t=0.125 and t=48 hr.

Discussion

The mean concentrations of BOD_5, COD, NH_4-N and chloride in landfill leachate accepted at the two study sites examined were consistent with values reported in literature for intermediate landfills (Frascari et al., 2004). The leachate volumetric loading regime had no impact on WWTP performance and effluent concentrations at Site 1 over the study period. Changing leachate loading regime at Site 2 from high to low shock loads increased NH_4-N removal efficiency and decreased effluent NH_4-N concentrations. Wastewater treatment plant managers must ensure that the final discharge to receiving waters is within the maximum permissible effluent concentrations or emission limit values (ELVs) set by the relevant authority. Wastewater treatment plant ELVs depend on the size and water quality status of the waterbody receiving the treated effluent and are unique to each WWTP. Effluent concentrations were lower at Site 1 with an ELV of 1 mg NH_4-N L^{-1} compared to Site 2 with an ELV of 10 mg NH_4-N L^{-1}; however, concentrations exceeded ELVs for Site 1 for all loading regimes examined and not Site 2. There was a correlation between WWTP VLR_i and effluent NH_4-N for Site 2 (R^2=0.68; p<0.05) but not for Site 1. These results demonstrate the challenges faced in treating landfill leachate in WWTPs with low ELVs. Future reductions to ELVs pose a significant threat to continued co-treatment of landfill leachate worldwide.

Leachate-derived NH_4-N accounted for 18% and 32% of TN treated at Sites 1 and 2, respectively. Therefore, leachate co-treatment has the potential to have an adverse impact on aeration requirements, nitrification efficiency and WWTP operating cost, as demonstrated at Site 2. Observed final discharge NO_3-N concentrations indicate that nitrification occurred at Site 1 (Figure 2), although there were no significant differences between loading regimes. Nitrate-N concentrations in the final discharge were highest during the drip-feed phase, indicating that leachate improved plant performance compared to no-leachate and shock loading regimes. At Site 2 final discharge NO_3-N concentrations were greater during the low leachate loading period, possibly indicating the inhibition of ammonium oxidizing bacteria during the high leachate loading period.

The batch experiments were in agreement with site monitoring results and demonstrate that intermediate age leachate loaded at volumetric ratios up to 4% or approximately 50% of total WWTP NH_4-N loading do not significantly inhibit nitrification processes (Figure 4). These findings have significant implications for WWTPs accepting young leachate similar to LL3 with high NH_4-N concentrations, as co-treatment at recommended VLRs may inhibit nitrification processes, as demonstrated in the current study. When using a volumetric loading rate of >4% (which corresponded to an initial concentration of approximately over 350 mg NH_4-N L^{-1} when LL3 was added to wastewater from Sites 1 and 3) nitrification inhibition occurred. It was not possible to determine an appropriate NH_4-N based leachate loading recommendation. However, a loading rate of 2% (approximately 90% of total WWTP NH_4-N load) may be more appropriate for the young leachate. This could vary between leachates depending on NH_4-N concentration and presence of other inhibitory compounds which were not observed in levels likely to cause? nitrification in this study (Table 4). The results of the beaker experiment were generally in agreement with the results from the site monitoring conducted during the current study (Figure 2) and previous studies (Kalka, 2012: Ye et al., 2014). These results demonstrate that hydraulic loading-based acceptance criteria recommendations are not appropriate when co-treating leachate with municipal wastewater, unless leachate NH_4-N composition is considered and known in advance of acceptance.

Addition of intermediate and young leachate to wastewater MLSS in beaker experiments increased initial NH_4-N concentrations compared to the control. Addition of leachate to wastewater MLSS was observed to increase initial alkalinity concentrations (t=0.125 h) compared to the control, but these increases were not statistically significant. Addition of intermediate age leachate had no impact on final alkalinity (t=48 hr), but young leachate added at all rates examined, significantly increased alkalinity compared to the control ($p<0.05$). Alkalinity was observed to decrease steadily in all beakers, reaching a plateau at approximately 6 hr. This indicates most of the nitrification occurred within the first 6 hours of the batch experiment.

Effluent NO_3-N concentrations indicate that nitrification occurred in all beakers (Figure 3) with the exception of leachate from Site 1 co-treated with wastewater from Site 1 and young leachate co-treated with wastewater from Site 1 and 3 when added at 10% ($p<0.05$). It is likely that insufficient alkalinity in the wastewater collected from Site 1 caused nitrification inhibition, as there was insufficient alkalinity present to ensure that complete nitrification occurred (Tchobanoglous et al., 2004). Inhibition in young leachate (10%) treatments for both wastewaters was likely caused by leachate toxicity, as alkalinity was not depleted entirely. In a subsequent experiment (unpublished data), leachate was pre-treated with ferric chloride ($FeCl_3$) and decanted before being co-treated with wastewater from Site 3 at 4% in a beaker experiment. Coagulation did not have any impact on initial NH_4-N concentration; however, 48 hr NH_4-N concentration was lower than untreated leachate ($p<0.05$), indicating that coagulation in WWTPs could result in a decrease in ammonium concentration in effluent. It was not possible to determine the cause of this decrease in toxicity; however, this indicates that NH_4-N toxicity alone was not the cause. These results indicate the need for site-specific nitrification trials to be conducted when accessing the potential impact of leachate acceptance, especially for young leachate.

Conclusions

These results demonstrate the complexity of recommending appropriate management practices for WWTPs accepting landfill leachate. Throughout the world, landfilling is in decline and landfill leachate has become a legacy problem. Unmanned landfill sites will require sustainable leachate treatment options to be developed. These findings indicate that although co-treatment of landfill leachate at WWTPs may be appropriate in some circumstances, the inherent variability in leachate composition and treatability necessitates a conservative approach. The main findings of this study are as follows:

1. Leachate loading regimes examined were found to be appropriate for effective treatment of intermediate age landfill leachate in the WWTPs examined, but co-treatment may not be suitable in WWTPs with low NH_4-N and TN ELVs.

2. Intermediate leachate, loaded at volumetric ratios of up to 4% or 50% of total WWTP NH_4-N loading, did not significantly inhibit nitrification processes.
3. Young leachate, loaded at volumetric ratios greater than 2% or approximately 90% of WWTP NH_4-N load, resulted in a significant decrease in nitrification.
4. Hydraulic loading-based acceptance criteria recommendations are not appropriate when co-treating young leachate with municipal wastewater, unless leachate NH_4-N composition is considered and known in advance of acceptance. Site-specific inhibition experiments may be necessary to determine appropriate loading rates.
5. Nitrogen loading should be considered when estimating the cost of leachate treatment, as leachate may comprise up to 48% of TN and 32% of NH_4-N loading, accounting for a significant portion of WWTPs aeration requirements.

Acknowledgements

The authors wish to thank the Irish Environmental Protection Agency for funding this project (EPA Research Code: 2013-W-FS-13) and all stakeholders for facilitating sample collection and providing data for the study.

References

Ağdağ, O. N. and Sponza, D. T. (2005) 'Anaerobic/aerobic treatment of municipal landfill leachate in sequential two-stage up-flow anaerobic sludge blanket reactor (UASB)/completely stirred tank reactor (CSTR) systems', Process Biochemistry, 40(2), pp. 895-902.

APHA (2012) 'Standard Methods for the Examination of Water and Wastewater. American Public Health Association (APHA), Washington.'.

Brennan, R., Healy, M., Morrison, L., Hynes, S., Norton, D. and Clifford, E. (2015) 'Management of landfill leachate: The legacy of European Union Directives', Waste Management.

Çeçen, F. and Aktaş, Ö. (2004) 'Aerobic Co-Treatment of Landfill Leachate with Domestic Wastewater', Environmental Engineering Science, 21(3), pp. 303-312.

Chofqi, A., Younsi, A., Lhadi, E. K., Mania, J., Mudry, J. and Veron, A. (2004) 'Environmental impact of an urban landfill on a coastal aquifer (El Jadida, Morocco)', Journal of African Earth Sciences, 39(3-5), pp. 509-516.

Diamadopoulos, E., Samaras, P., Dabou, X. and Sakellaropoulos, G. P. (1997) 'Combined treatment of landfill leachate and domestic sewage in a sequencing batch reactor', Water Science and Technology, 36(2–3), pp. 61-68.

EC (2001) 'Council Directive concerning urban-waste-water traetment. Available at http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:31999L0031 on 16th May 2015.'.

EC (2007) European Comission, DG Environment. Follow-up study on the implementation of Directive 1999/31/EC on the landfill of waste in EU-25.

EC (2008) 'Official Journal of the European Union. Waste Framework Directive. Available at: http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32008L0098&from=EN on 18th May 2015.'.

Ferraz, F. M., Povinelli, J., Pozzi, E., Vieira, E. M. and Trofino, J. C. (2014) 'Co-treatment of landfill leachate and domestic wastewater using a submerged aerobic biofilter', Journal of Environmental Management, 141(0), pp. 9-15.

Frascari, D., Bronzini, F., Giordano, G., Tedioli, G. and Nocentini, M. (2004) 'Long-term characterization, lagoon treatment and migration potential of landfill leachate: a case study in an active Italian landfill', Chemosphere, 54(3), pp. 335-343.

Gerardi, M. H. (2002) Nitrification and denitrification in the activated sludge process. Wiley-Interscience. John Wiley and Sons, Inc., New York.

Gupta, A., Zhao, R., Novak, J. T. and Goldsmith, C. D. (2014) 'Variation in organic matter characteristics of landfill leachates in different stabilisation stages', Waste Management & Research, pp. 0734242X14550739.

Henze, M., Harremoes, P., La Cour Jansen, J. and Arvin, E. (2002) Wastewater Treatment: Biological and Chemical Processes. Second Edition.

Kalka, J. (2012) 'Landfill leachate toxicity removal in combined treatment with municipal wastewater', ScientificWorldJournal, 2012, pp. 202897.

Knox, K., Kowlesser, P. and Rampersad, V. (2015) 'A case study of leachate management at tropical landfills: Mare Chicose, Mauritius', Proceedings Sardinia 2015, Fifteenth International Waste Management and Landfill Symposium S. Margherita di Pula, Cagliari, Italy; 5 – 9 October 2015.

Kurniawan, T. A., Lo, W. H. and Chan, G. Y. (2006) 'Physico-chemical treatments for removal of recalcitrant contaminants from landfill leachate', J Hazard Mater, 129(1-3), pp. 80-100.

Marshall, R. (2009) Guidance on Monitoring of Landfill Leachate, Groundwater and Surface Water. Environmental Agency. Available: file:///C:/Users/0109448s/Downloads/environmental_permitting_regulations_inert_waste_guidance.pdf, accessed 25th March 2015.

Marzougui, A. and Ben Mammou, A. (2006) 'Impacts of the dumping site on the environment: Case of the Henchir El Yahoudia Site, Tunis, Tunisia', Comptes Rendus Geoscience, 338(16), pp. 1176-1183.

McCarthy, S., Moriarty, J., O'Riordan, D. and O'Leary, G. (2010) 'The Environmental Protection Agency. Focus on landfilling in Ireland'.

Met Eireann (2015) 'Temperature data http://www.met.ie/climate-ireland/surface-temperature.asp assessed 14th Janurary 2016.'.

Mukherjee, S., Mukhopadhyay, S., Hashim, M. A. and Sen Gupta, B. (2014) 'Contemporary Environmental Issues of Landfill Leachate: Assessment and Remedies', Critical Reviews in Environmental Science and Technology, 45(5), pp. 472-590.

Renou, S., Givaudan, J. G., Poulain, S., Dirassouyan, F. and Moulin, P. (2008) 'Landfill leachate treatment: Review and opportunity', Journal of Hazardous Materials, 150(3), pp. 468-93.

Slack, R. J., Gronow, J. R. and Voulvoulis, N. (2005) 'Household hazardous waste in municipal landfills: contaminants in leachate', Science of The Total Environment, 337(1–3), pp. 119-137.

Stegmann, R., Heyer, K. U. and Cossu, R. (2005) 'Leachate Treatment', Proceedings Sardinia 2005, Tenth International Waste Management and Landfill Symposium S. Margherita di Pula, Cagliari, Italy; 3 - 7 October 2005

Tatsi, A. A. and Zouboulis, A. I. (2002) 'A field investigation of the quantity and quality of leachate from a municipal solid waste landfill in a Mediterranean climate (Thessaloniki, Greece)', Advances in Environmental Research, 6(3), pp. 207-219.

Tchobanoglous, G., Burton, F. L. and Stensel, H. D. (2004) 'Wastewater Engineering: Treatment and Reuse 4th Edition'.

Wang, Y. (2013) Leachate management in the aftercare period of municipal waste landfills. PhD, Aalto University [Online] Available at: http://lib.tkk.fi/Diss/2013/isbn9789526051413/isbn9789526051413.pdf (Accessed.

Ye, Z.-L., Xie, X., Dai, L., Wang, Z., Wu, W., Zhao, F., Xie, X., Huang, S., Liu, M. and Chen, S. (2014) 'Full-scale blending treatment of fresh MSWI leachate with municipal wastewater in a wastewater treatment plant', Waste Management, 34(11), pp. 2305-2311.

Zhang, L., Li, A., Lu, Y., Yan, L., Zhong, S. and Deng, C. (2009) 'Characterization and removal of dissolved organic matter (DOM) from landfill leachate rejected by nanofiltration', waste management, 29(3), pp. 1035-1040.

Table 1 Study site wastewater treatment plant operational information (Annual data 2013)

WWTP identifier		Site 1	Site 2
Design P.E.	PE	5,000	25,000
Operating P.E.		2,000	19,000
Leachate treated at WWTP		LL1	LL2
Transportation method		Tanker	Sewer
Leachate entry point		Aeration tank	Sewer
Leachate pre-treatment		None	None
Annual volume leachate accepted	m^3yr^{-1}	7,302	47,744
Yearly average leachate influent volume as percentage of total effluent	%	1.17	2.3

WWTP: wastewater treatment plant; P.E.: population equivalent; LL1 and 2: landfill leachate from sites 1, and 2 respectively

Table 2 Study site landfill leachate characterisation

		Leachate entering Site 1			Leachate entering Site 2		
		Range	Mean	Std. Dev.	Range	Mean	Std. Dev.
pH	pH	6.8-7.8	7.3	1	7.8-8	8	0.12
Conductivity	µs cm^{-1}	6840-6870	6855	21	3117-4578	3803	735
Ammonium as N	mg L^{-1}	245-378	311[a]	67	120-246	183[a]	89
Total nitrogen	mg L^{-1}	279-429	351[a]	75	130-380	253[a]	130
BOD_5	mg L^{-1}	8-20	14	6	100-700	396	300
COD	mg L^{-1}	274-420	361[a]	77	698-2190	1362	759
BOD_5:COD ratio		0.03-0.05	0.04	0.01	0.14-0.32	0.26	0.1
Alkalinity	mg L^{-1}	10-1083	547	759	1306-1918	1554	322
Chloride	mg L^{-1}	130-201	163	36	160-371	290	114
Sulphate	mg L^{-1}	109-320	210	106	7.2-93	43	45
SS	mg L^{-1}	12-89	44[a]	40	45-126	79[a]	42

BOD_5: 5-day biochemical oxygen demand; COD chemical oxygen demand; Sig.: significance level; letters denote leachate concentrations which are not significantly different to each other when comparing between leachates.

Table 3 Wastewater treatment plant influent and effluent daily loads (kg d^{-1}) and percentage removal efficiency at each study site WWTP.

WWTP	Reg.	Average volume m^3d^{-1}	BOD_5 (kgd^{-1}) Inf	Eff	%	COD (kgd^{-1}) Inf	Eff	%	TIC_f (kgd^{-1}) Inf	Eff	%	TOC_f (kgd^{-1}) Inf	Eff	%	TN_f (kgd^{-1}) Inf	Eff	%	NH_4-N (kgd^{-1}) Inf	Eff	%
Site 1	D	2040	319	2	99	487	68	91	27	13	34	32	10	55	26	42	-2	24	2	91
	N	2470	512	9	97	905	97	88	37	26	16	46	11	47	49	30	39	44	3	96
	S	2400	600	7	99	803	75	90	80	39	55	56	12	62	46	49	8	40	3	95
Site 2	S_H	6450	1926	146	91	3742	394	88	324	144	52	436	106	75	238	174	20	200	30	87
	S_L	6210	1069	71	94	4082	270	93	294	79	69	323	72	77	217	149	29	191	4	98

WWTP: Wastewater treatment plant; Reg.: landfill leachate loading regime; D: drip feed; N: No leachate; S: shock load; L: low loading; H: high loading; BOD: biochemical oxygen demand; COD: chemical oxygen demand; TIC_f: total filtered inorganic carbon; TOC_f: total filtered organic carbon; TN: total nitrogen; NH_4-N: ammonium nitrogen.

Table 4 Metal concentrations in WWTP influent, effluent and landfill leachate accepted at each study site WWTP.

Parameter		Cadmium*	Lead*	Mercury*	Nickel*	Arsenic	Chromium	Copper
Units		mg L^{-1}	mg L^{-1}	mg L^{-1}	mg L^{-1}	mg L^{-1}	mg L^{-1}	mg L^{-1}
Site 1	Influent (before leachate added to aeration tank)	0.3^a (0)	1.7^a (1.09)	0.06^a(0)	6.3^a(2.9)	1.06^a (0.13)	5.7^a (4.6)	0.01^a (0.01)
	Effluent	0.3^a (0)	1.1^a (0.51)	0.11^a(0.17)	5.6^a(1.47)	1 $(0)^a$	4.1^a (1.02)	0.01^a (0)
	Leachate at point of entry to sewer	0.6^a (0)	3.17 (1)	0.12a(0)	57(5)	33 (1)	93 (23)	0.03 (0)
Site 2	Influent (including leachate which was in sewer)	0.3^a (0)	4.41 (2.15)	0.08^a (0.03)	5.7(1.85)	1.55^a (1.14)	6.2^a (5.7)	0.12 (0.05)
	Effluent	0.3^a (0)	0.91^a (0.03)	0.06^a(0)	4.57(0.29)	1.01^a (0.03)	4.1^a (2.8)	0.04^a (0.03)
	Leachate at point of entry to WWTP	0.23^a (0.1)	2.25^a (1.85)	0.06(0.03)	31(16.5)	22 (10.03)	63 (29)	0.02^a (0.01)
	Nitrification inhibiting value**	1	0.5	0.1	0.5	0.05-0.1	1	0.1-0.35

Standard deviation in parenthesis; $p<0.05$: significance level; letters denote leachate concentrations which are not significantly different to each other when comparing between leachates.*metals on priority substances list (EC, 2008a); **Hanmer et al. (1983).

Table 5 Beaker experiment initial leachate and MMLS characterisation

	COD	NH_4-N	Alkalinity	TON	MLSS	VSS
Activated sludge from Site 1	3664	4.76	62.5	0.63	3265	2585
Activated sludge from Site 3	3232	5.93	34	6.94	1475	1075
Leachate from landfill 1 (LL1)	1236	134	700	1.034	135	60
Leachate from landfill 3 (LL3)	11373	2800	7820	1.1	360	195

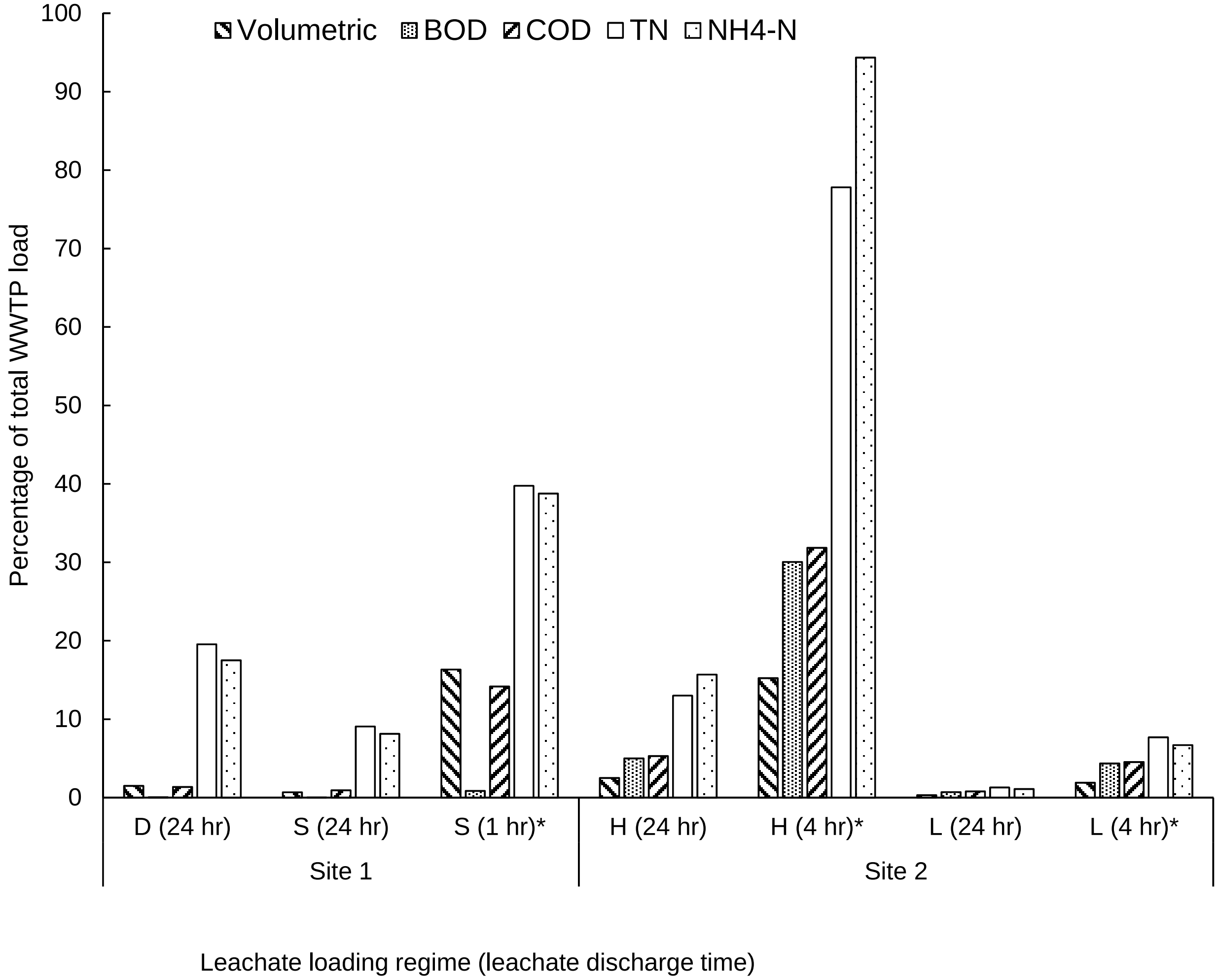
Units: mg L^{-1}; WW: Wastewater; LL: landfill leachate; COD: chemical oxygen demand; NH_4-N: ammonium nitrogen; TON: total oxidized nitrogen (NO_3-N+NO_2-N); MLSS: mixed liquor suspended solids; VSS: volatile suspended solids.

Table 6 Beaker experiment chemical oxygen demand (COD), pH and dissolved oxygen (DO).

		COD	pH		Dissolved oxygen	
		mg L^{-1}	pH units		mg L^{-1}	
	Volume	48 hr	0.125 hr	48 hr	0.125 hr	48 hr
Site 1 w/w + LL1	0%	3750 (1490)	6.3 (0)	5.3 (0)	9 (0.4)	9.9 (0.2)
	2%	3250 (1070)	6.5 (0.2)	5.5 (0)	9.1 (0.2)	10 (0.6)
	4%	2660 (2090)	6.8 (0.1)	5.3 (0.1)	8.6 (0.2)	9.8 (0.2)
	10%	4630 (695)	7.4 (0)	5.3 (0.1)	7.5 (1.5)	9.7 (0.2)
Site 1 w/w + LL3	0%	2020 (2290)	6 (0.2)	5.6 (0.2)	8.3 (1.2)	11.5 (0.4)
	2%	2430 (1780)	7.1 (0.2)	5.5 (0.7)	8.6 (1.3)	11.2 (0.3)
	4%	2570 (977)	7.6 (0.2)	6.8 (0.7)	9.5 (0.2)	10.4 (0.4)
	10%	2580 (1960)	8.1 (0.1)	9.4 (0.1)	9 (1)	10.2 (1.5)
Site 3 w/w + LL1	0%	3910 (1340)	8 (0.2)	8 (0)	7.9 (0.1)	2.5 (0.3)
	2%	4000 (2320)	7.8 (0.2)	8 (0.1)	8.1 (0.2)	1.9 (0)
	4%	3850 (2160)	7.5 (0.1)	8 (0.1)	6 (1)	1.6 (0.3)
	10%	5910 (411)	7.3 (0.3)	7.8 (0.2)	9.5 (15.2)	1.5 (0.1)
Site 3 w/w + LL3	0%	5040 (2010)	7 (0.1)	6.8 (0.2)	4.2 (0.7)	8.3 (1.7)
	2%	4610 (994)	7.6 (0.1)	6.7 (0.3)	3 (2)	8.5 (0.8)
	4%	2360 (1560)	7.9 (0.2)	6.9 (0.7)	4.1 (0.6)	8.1 (1.7)
	10%	6360 (928)	8.4 (0.2)	8.8 (0.1)	5.8 (2.2)	8.9 (0.6)

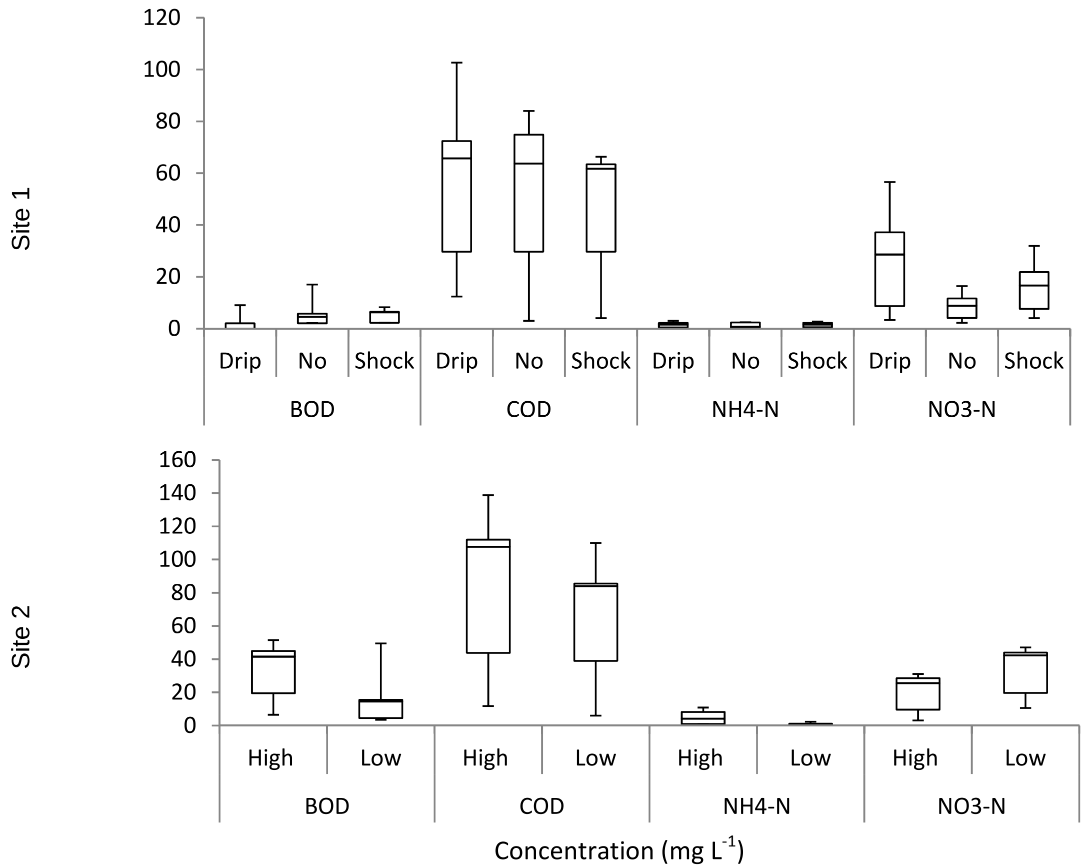
Standard deviation in parenthesis; $p<0.05$: significance level; *different to control and 0%.

Figure 1 Bar chart showing leachate daily and instantaneous volumetric loading rates (VLR and VLR_i), BOD_5, COD, TN and NH_4-N mass loads as a percentage of WWTP influent mass.



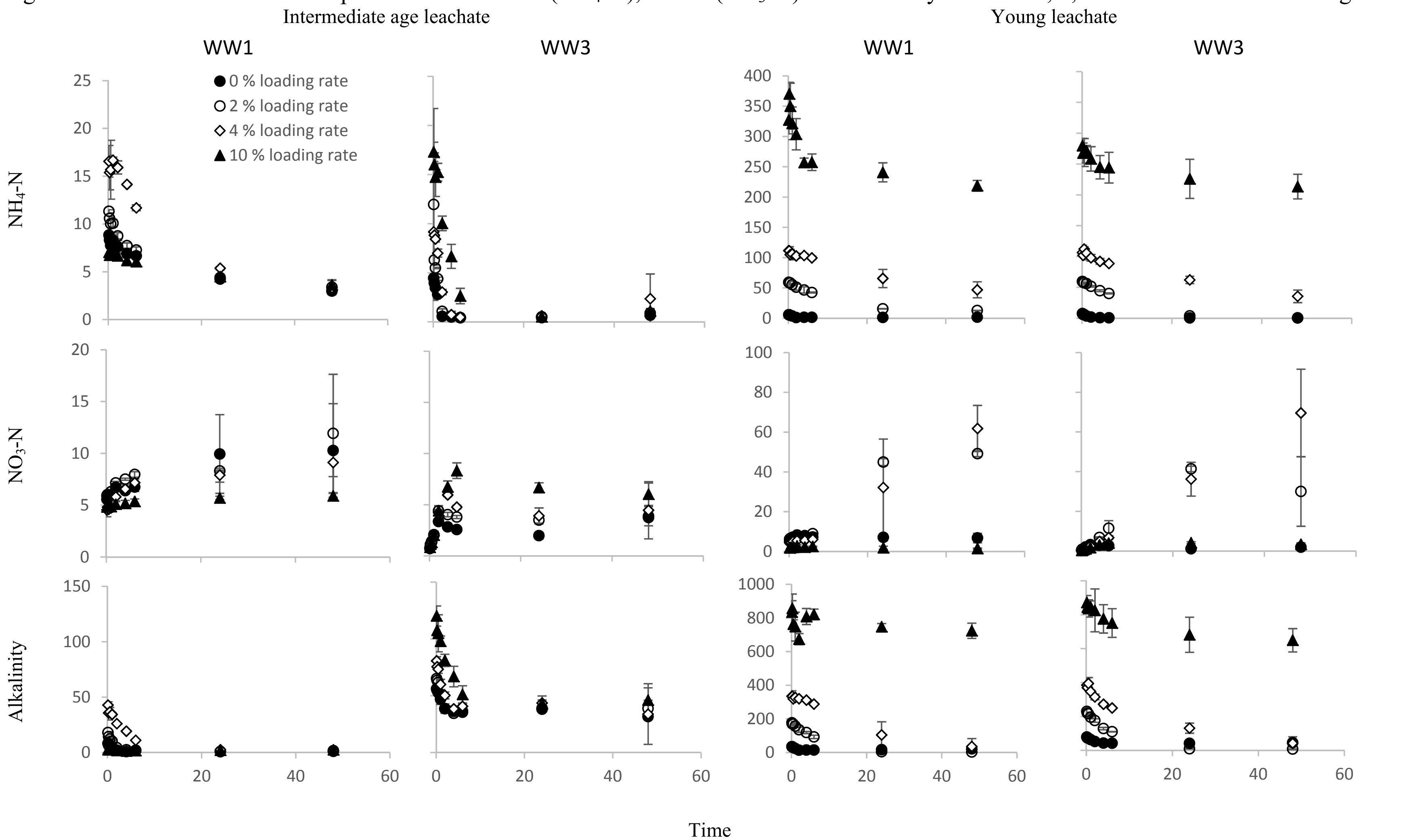
Units: %; D: drip feed; S: shock load; L: low loading; H: high loading; BOD: biochemical oxygen demand; COD: chemical oxygen demand; TN total nitrogen; NH_4-N: ammonium nitrogen; VLR: volumetric loading rate. WWTP: wastewater treatment plant; *denotes VLR_i which in the instantaneous volumetric rate determined by expressing the volume of leachate treated as a percentage of the volume of effluent treated during the time the leachate was discharged to the WWTP/sewer from the tanker or on-site storage tank.

Figure 2 Boxplot showing wastewater treatment plant effluent.



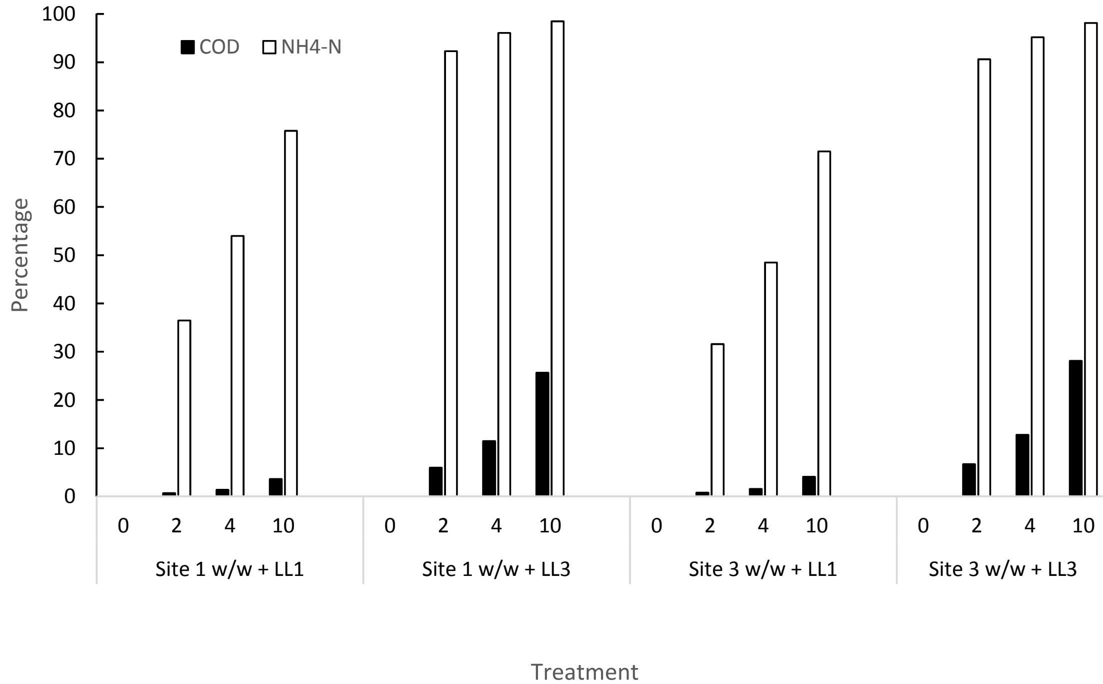
Units: mg L^{-1}; D: drip feed; N: No leachate; S: shock load; L: low loading; H: high loading; BOD: biochemical oxygen demand; COD: chemical oxygen demand; NH_4-N: ammonium nitrogen; nitrate (NO_3-N).

Figure 3 Nitrification inhibition experiment ammonium (NH_4-N), nitrate (NO_3-N) and alkalinity trends at 0, 2, 4 and 10% leachate loading rates.



Units: mg L^{-1}; Error bars denote standard deviation; WW: wastewater; LL: landfill leachate; NH_4-N: ammonium nitrogen; NO_3-N: Nitrate nitrogen.

Figure 4 Bar chart showing leachate volumetric loading rate (VLR), COD and NH_4-N mass loads as a percentage of WWTP influent mass for laboratory batch experiments.



Units: %; COD: chemical oxygen demand; NH_4-N: ammonium nitrogen; WWTP: wastewater treatment plant.