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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
Publication Information	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. <i>Journal of Environmental Management</i> , 188, 64-72. doi: http://dx.doi.org/10.1016/j.jenvman.2016.11.055
Publisher	Elsevier
Link to publisher's version	http://dx.doi.org/10.1016/j.jenvman.2016.11.055
Item record	http://hdl.handle.net/10379/6208
DOI	http://dx.doi.org/10.1016/j.jenvman.2016.11.055

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1 Published as: Brennan, R.B., Clifford, E., Devroedt, C., Morrison, L., Healy, M.G. 2017.
2 Treatment of landfill leachate in municipal wastewater treatment plants and impacts on
3 effluent ammonium concentrations. Journal of Environmental Management 188: 64 – 72.
4 <http://dx.doi.org/10.1016/j.jenvman.2016.11.055>
5

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

8
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19
20 **Abstract**

21
22 Landfill leachate is the result of water percolating through waste deposits that have
23 undergone aerobic and anaerobic microbial decomposition. In recent years, increasingly
24 stringent wastewater discharge requirements have raised questions regarding the efficacy of
25 co-treatment of leachate in municipal wastewater treatment plants (WWTPs). This study
26 aimed to (1) examine the co-treatment of leachate with a 5-day biochemical oxygen demand
27 (BOD₅): chemical oxygen demand (COD) ratio less than or slightly greater than 0.26
28 (intermediate age leachate) in municipal WWTPs (2) quantify the maximum hydraulic and

29 mass (expressed as mass nitrogen or COD) loading of landfill leachate (as a percentage of the
30 total influent loading rate) above which the performance of a WWTP may be inhibited, and
31 (3) quantify the impact of a range of hydraulic loading rates (HLRs) of young and
32 intermediate age leachate, loaded on a volumetric basis at 0 (study control), 2, 4 and 10%
33 (volume landfill leachate influent as a percentage of influent municipal wastewater), on the
34 effluent ammonium concentrations. The leachate loading regimes examined were found to be
35 appropriate for effective treatment of intermediate age landfill leachate in the WWTPs
36 examined, but co-treatment may not be suitable in WWTPs with low ammonium-nitrogen
37 ($\text{NH}_4\text{-N}$) and total nitrogen (TN) emission limit values (ELVs). In addition, intermediate
38 leachate, loaded at volumetric rates of up to 4% or 50% of total WWTP $\text{NH}_4\text{-N}$ loading, did
39 not significantly inhibit the nitrification processes, while young leachate, loaded at
40 volumetric rates greater of than 2% (equivalent to 90% of total WWTP $\text{NH}_4\text{-N}$ loading),
41 resulted in a significant decrease in nitrification. The results show that current hydraulic
42 loading-based acceptance criteria recommendations should be considered in the context of
43 leachate $\text{NH}_4\text{-N}$ composition. The results also indicate that co-treatment of old leachate in
44 municipal WWTPs may represent the most sustainable solution for ongoing leachate
45 treatment in the cases examined.

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

48

49 **Introduction**

50

51 Landfill leachate is the result of water percolating through waste deposits that have
52 undergone aerobic and anaerobic microbial decomposition (Chofqi et al., 2004; Gupta et al.,
53 2014; Mukherjee et al., 2014). Its composition is a function of the type of waste in the
54 landfill, landfill age, climate conditions, and hydrogeology of the landfill site (Chofqi et al.,
55 2004; Slack et al., 2005). A landfill site will produce leachate throughout its working life and
56 also for several hundred years after it is decommissioned (Wang, 2013). The control of a
57 landfill site, and appropriate treatment of the leachate it produces, is paramount in the
58 protection of the surrounding environment, as leachate contamination of groundwater, rivers,
59 lakes and soils has the potential to negatively affect local habitats, resources and human
60 health (Ağdağ and Sponza, 2005; Marshall, 2009).

61

62 The European Union (EU) Landfill Council Directive 1999/31/EC (EC, 2001) and
63 subsequent waste management legislation (EC, 2008) have resulted in major changes in the
64 waste management sector in Europe over the last 30 years. The Landfill Directive sets targets
65 that (1) reduce the percentage of waste that can be consigned to landfill for each member
66 state (2) decrease the quantity of biodegradable municipal waste sent to a landfill, and (3)
67 places responsibility on landfill owners to budget for the aftercare of a landfill site for a
68 minimum of 30 years after operation has ceased. Prior to the implementation of this
69 Directive, landfilling across the EU was unregulated and poorly planned (EC, 2007). The
70 Directive has resulted in dramatic improvements in the manner in which landfills, and
71 specifically landfill leachate, is managed (McCarthy et al., 2010; Brennan et al., 2015). While
72 there has been a decline in landfilling in recent years, leachate generation is a legacy
73 problem, and the treatment of leachate is the major management issue facing landfill

74 operators (Zhang et al., 2010; Brennan et al., 2015). Many landfills are not located close to
75 suitable receiving waters (Knox et al., 2015). Therefore, the most sustainable option may be
76 to transfer leachate to wastewater treatment plants (WWTPs) for final treatment.

77

78 Leachate contains high levels of 5-day biochemical oxygen demand (BOD₅), chemical
79 oxygen demand (COD), ammonium-nitrogen (NH₄-N), chloride (Cl), sodium (Na), potassium
80 (K), nitrogen (N), boron (B), solvents, phenols, hardness and metals, including iron (Fe),
81 manganese (Mn), zinc (Zn), copper (Cu), cobalt (Co), chromium (Cr), nickel (Ni), cadmium
82 (Cd) and lead (Pb) (Tatsi et al., 2003; Chofqi et al., 2004; Ağdağ and Sponza, 2005;
83 Marzougui and Mammou, 2006). Young leachate (generated in operational landfills or
84 landfills closed for less than five years (Renou et al., 2008)) is highly biodegradable and
85 exhibits COD and NH₄-N concentrations of up to 80,000 and 3,100 mg L⁻¹, respectively, and
86 BOD₅:COD ratios of up to 0.7 (Stegmann et al., 2005). As a result, biological treatment
87 methods are reasonably efficient in the removal of COD, NH₄ and metals (Kurniawan et al.,
88 2006). Conversely, older (stabilised) leachate is less biodegradable and contains
89 methanogenic leachate with BOD₅:COD ratios < 0.2 (Stegmann et al., 2005), and therefore is
90 not as efficiently treated using biological methods. In the current paper, landfills are defined
91 as young (operational/closed less than five years), intermediate (closed more than five year
92 but less than 10), and old (closed more than ten years) (after Renou et al., 2008).

93

94 To date, there has been limited work regarding the impacts of co-treatment of landfill
95 leachate and municipal wastewater in WWTPs (Renou et al., 2008), and studies have been
96 largely limited to laboratory-scale batch experiments (Diamadopoulos et al., 1997; Çeçen and
97 Aktaş, 2004; Capodici et al., 2014; Wu et al., 2015; Mojiri et al., 2016). These studies have
98 generally concluded that WWTP removal efficiency is not adversely affected, provided the

99 total hydraulic loading of leachate does not exceed 10% of the total municipal wastewater
100 entering the WWTP. However, at these volumetric loading rates effluent NH₄-N and total
101 nitrogen (TN) may be significantly impacted due to their relatively high concentrations in
102 landfill leachate (Diamadopoulos et al., 1997; Ye et al., 2014; Ferraz et al., 2014). The lack of
103 recent studies examining co-treatment of leachate in operational municipal WWTPs is a
104 concern for WWTP managers, as wastewater effluent is subject to increasingly stringent
105 legislation in the EU. There is a concern that recommendations based on laboratory studies
106 and not site-specific data, may result in failures to achieve compliance.

107

108 Studies have demonstrated that co-treatment of young leachate with municipal wastewater
109 does not adversely affect WWTP performance (Diamadopoulos et al., 1997; Kalka, 2012; Ye
110 et al., 2014); however, the effect of old landfill leachate (BOD₅:COD < 0.01; Renou et al.,
111 2008) has not been widely examined with the exception of Del Borghi et al. (2003), who
112 concluded that old leachate should mixed with young leachate before treatment. The current
113 study (1) examines the co-treatment of leachate with a BOD₅: COD ratio less than or slightly
114 greater than 0.26 (intermediate age leachate) in municipal WWTPs and attempts to quantify
115 the maximum hydraulic and mass (expressed as mass nitrogen or COD) loading of landfill
116 leachate (as a percentage of the total influent loading rate) above which the performance of a
117 WWTP may be inhibited and (2) quantifies the impact of a range of volumetric loading rates
118 (VLRs) of young and intermediate age leachate, loaded on a volumetric basis at 0, 2, 4 and
119 10% (expressed as volume landfill leachate treated in the WWTP as a percentage of the total
120 influent wastewater to the WWTP), on NH₄-N removal. The study is thus focused on the
121 feeding strategy adoptable in order to minimize the adverse effects of landfill leachate
122 presence in the WWTP.

123

124 **Materials and Methods**

125

126 *Study sites*

127

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

133

134 *WWTP monitoring*

135

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

149

150 *Analysis of wastewater and landfill leachate*

151

152 Samples were analysed for BOD₅, COD, CODs, filtered total nitrogen (TN_f), filtered total
153 inorganic carbon (TIC_f), filtered total organic carbon (TOC_f), ortho-phosphorus (PO₄-P),
154 nitrate-nitrogen (NO₃-N), nitrite-nitrogen (NO₂-N), alkalinity, sulphate, chloride, NH₄-N and
155 suspended solids (SS). All analyses were conducted in accordance with the standards method
156 for the examination of water and wastewater (APHA et al., 2012). Conductivity and pH were
157 determined using a SAC950 sample changer and a Titralab 870. Total metal concentrations
158 for Cu, Cd, Cr, As, Pb, Hg, and Ni were determined by Inductively Coupled Plasma Mass
159 Spectrometry (ICP-MS) (Agilent 7500a Technologies Inc. USA) following microwave
160 digestion (CEM Discover SPD Microwave Digester) using Trace Metal Grade Nitric Acid
161 (Fisher, UK).

162

163 *Nitrification inhibition batch experiments*

164

165 Laboratory batch experiments, conducted to supplement the results of the WWTP study,
166 examined the impact of various landfill leachate on NH₄-N removal in controlled
167 experiments. Landfill leachate LL1 and LL3 were added to a mixed liquor suspended solids
168 (MLSS) samples from Sites 1 and 3 at volumetric loading rates (volume LL/volume MLSS
169 sample) of 0, 2, 4 and 10% (n=3 for each experiment). Landfill leachate and MLSS were
170 collected, transported to the laboratory, and stored at 4°C. Batch experiments were conducted
171 within 12 hours of sample collection. Experiments were conducted in triplicate using 2 L-
172 capacity beakers in a cold room with a controlled temperature of 10°C, which is similar to
173 mean air temperatures observed in Ireland (Met Eireann, 2015). Wastewater/wastewater and

174 leachate mixtures were added to the beakers and immediately following this, aeration
175 commenced using an air-stone placed at the base of each beaker. Beakers were constantly
176 aerated with an air flow sufficient to ensure suspension of solids throughout the experiment.
177 Wastewater/wastewater and leachate mixture pH and dissolved oxygen (DO) were measured
178 and samples withdrawn from the beakers (2 mL) for alkalinity, NH₄-N and NO₃-N analysis at
179 t = 0.125, 0.25, 0.5, 1, 2, 4, 6, 24 and 48 hours. After 48 hours aeration ceased, and filtered
180 and unfiltered samples were taken for analysis for COD and CODs (soluble fraction of COD)
181 analysis.

182

183 *Data analysis*

184

185 Daily VLR was determined by expressing the daily volume of leachate treated as a
186 percentage of the daily effluent treated at the WWTP. The instantaneous leachate loading rate
187 (VLR_i) was determined by expressing the volume of leachate treated as a percentage of the
188 volume of effluent treated during the time the leachate was discharged to the WWTP/sewer
189 from the tanker or on-site storage tank. Daily leachate BOD₅, COD and NH₄-N mass loads
190 were also expressed as a percentage of daily WWTP influent BOD₅, COD and NH₄-N mass
191 loads. Data were analysed using ANOVA in SPSS (IBM SPSS Statistics 20 Core System,
192 Version 20). Beaker experimental data satisfied the normality assumption, while logarithmic
193 transformations were required for the site monitoring data to satisfy the normality
194 assumption, based on checking post-analysis residuals for normality and homogeneity of
195 variance.

196

197 **Results**

198

199 *Landfill leachate characterisation*

200

201 The range and mean concentrations of pH, conductivity, NH₄-N, TN, BOD₅, COD,
202 BOD₅:COD ratio, alkalinity, chloride, sulphate and SS in landfill leachate accepted at the two
203 study sites are shown in Table 2. Concentrations of inhibiting compounds such as NH₄-N
204 (Table 2), As and Cu (Table 4) were not above typical inhibitory thresholds (480 mg L⁻¹,
205 0.05-0.1 mg L⁻¹ and 0.1-0.35 mg L⁻¹, respectively) for nitrifying populations in inactivated
206 sludge (Gerardi, 2002; Henze et al., 2002).

207

208 *WWTP monitoring*

209

210 *Site 1*

211

212 Influent volume, COD, BOD₅, TIC_f, TOC_f, TN_f and NH₄-N daily mass loads and
213 concentrations did not significantly differ between the three loading regimes (drip-feed, no
214 leachate and shock loading; $p < 0.05$) (Table 3). There were no significant difference between
215 influent and effluent As, Cd, Cr, Cu, Pb, Hg, and Ni concentrations (Table 4). Daily carbon
216 loading rates were similar to VLR (Figure 1), with average daily leachate loading accounting
217 for less than 0.1% and 2% of total BOD₅ and COD loads to the WWTP throughout the study,
218 while average daily TN and NH₄-N loading accounted for a maximum of 9% and 8% of TN
219 and NH₄-N daily loads to the WWTP, respectively. The VLR_i was unchanged during the
220 drip-flow phase, but increased to 16% during the shock loading phase (Figure 1) while
221 instantaneous TN and NH₄-N loading increased to 40% and 39%, respectively. The leachate
222 loading regime at Site 1 did not have a statistically significant impact ($p < 0.05$) on percentage
223 removals of BOD₅, COD, TIC_f, TOC_f, TN_f, or NH₄-N (Table 3) or effluent concentrations

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

226

227 *Site 2*

228

229 Influent volume, COD, BOD₅, TIC_f, TOC_f, TN_f and NH₄-N mass loads and concentrations
230 did not significantly differ between high and low shock loading regimes ($p < 0.05$) (Table 3).

231 There were no significant difference between influent and effluent As, Cd, Cr, Cu, and Ni

232 concentrations, but there were significant differences in influent and effluent Pb and Hg

233 (Table 4). The VLR decreased from 2.5 to 0.3% when the loading regime was changed from

234 high to low leachate loading regime, while the equivalent daily BOD₅ loading ratios

235 decreased from 5% to 0.7%, COD from 5.3% to 0.8%, and NH₄-N from 16% to 1.1%. The

236 VLR_i decreased from 15.2 to 1.9% during the high and low leachate loading phases (Figure

237 1). The leachate loading regime at Site 2 did not significantly impact the COD and BOD₅

238 removals when comparison was made between the effluent from each leachate loading

239 regime (Table 3). However, TIC_f ($p < 0.05$), TOC_f ($p < 0.05$) and NH₄-N ($p < 0.001$) removals

240 increased significantly when the leachate loading regime was reduced from a high to a low

241 loading rate. Decreasing leachate loading resulted in decreased effluent NH₄-N

242 concentrations, with mean NH₄-N concentrations decreasing from 4.0 mg L⁻¹ during the high

243 loading period to 0.65 mg L⁻¹ during the low loading period ($p < 0.001$) (Figure 2).

244

245 *Laboratory batch experiments*

246

247 Initial COD_f, COD_t, NH₄-N, total oxidised nitrogen (TON), alkalinity, MSL and VSS

248 concentrations for leachate used in laboratory batch experiments are shown in Table 5.

249 Addition of intermediate and young leachate to MLSS increased initial $\text{NH}_4\text{-N}$ and alkalinity
250 concentrations ($t=0.125$ hr) compared to the control (Figure 3) for Site 1 wastewater and Site
251 3 wastewater. These increases were statistically significant for the young leachate, but not for
252 the intermediate age leachate ($p<0.05$). Ammonium and alkalinity concentrations were
253 observed to decrease relatively steadily until approximately 6 hr after the experiment started
254 (Figure 3). Following this, a plateau effect was observed, with little further decrease in $\text{NH}_4\text{-N}$
255 and alkalinity concentrations with time. However, young leachate, added at a volumetric
256 loading ratio of 4% or above, significantly increased $\text{NH}_4\text{-N}$ concentrations compared to the
257 control ($p<0.05$). Table 6 shows wastewater/wastewater and leachate mixture pH and DO at
258 $t=0.125$ and $t=48$ hr.

259

260 **Discussion**

261

262 The mean concentrations of BOD_5 , COD, $\text{NH}_4\text{-N}$ and chloride in landfill leachate accepted at
263 the two study sites examined were consistent with values reported in literature for
264 intermediate landfills (Frasconi et al., 2004). The leachate volumetric loading regime had no
265 impact on WWTP performance and effluent concentrations at Site 1 over the study period.
266 Changing leachate loading regime at Site 2 from high to low shock loads increased $\text{NH}_4\text{-N}$
267 removal efficiency and decreased effluent $\text{NH}_4\text{-N}$ concentrations. Wastewater treatment plant
268 managers must ensure that the final discharge to receiving waters is within the maximum
269 permissible effluent concentrations or emission limit values (ELVs) set by the relevant
270 authority. Wastewater treatment plant ELVs depend on the size and water quality status of
271 the waterbody receiving the treated effluent and are unique to each WWTP. Effluent
272 concentrations were lower at Site 1 with an ELV of $1 \text{ mg NH}_4\text{-N L}^{-1}$ compared to Site 2 with
273 an ELV of $10 \text{ mg NH}_4\text{-N L}^{-1}$; however, concentrations exceeded ELVs for Site 1 for all

274 loading regimes examined and not Site 2. There was a correlation between WWTP VLR_i and
275 effluent NH₄-N for Site 2 ($R^2=0.68$; $p<0.05$) but not for Site 1. These results demonstrate the
276 challenges faced in treating landfill leachate in WWTPs with low ELVs. Future reductions to
277 ELVs pose a significant threat to continued co-treatment of landfill leachate worldwide.

278

279 Leachate-derived NH₄-N accounted for 18% and 32% of TN treated at Sites 1 and 2,
280 respectively. Therefore, leachate co-treatment has the potential to have an adverse impact on
281 aeration requirements, nitrification efficiency and WWTP operating cost, as demonstrated at
282 Site 2. Observed final discharge NO₃-N concentrations indicate that nitrification occurred at
283 Site 1 (Figure 2), although there were no significant differences between loading regimes.
284 Nitrate-N concentrations in the final discharge were highest during the drip-feed phase,
285 indicating that leachate improved plant performance compared to no-leachate and shock
286 loading regimes. At Site 2 final discharge NO₃-N concentrations were greater during the low
287 leachate loading period, possibly indicating the inhibition of ammonium oxidizing bacteria
288 during the high leachate loading period.

289

290 The batch experiments were in agreement with site monitoring results and demonstrate that
291 intermediate age leachate loaded at volumetric ratios up to 4% or approximately 50% of total
292 WWTP NH₄-N loading do not significantly inhibit nitrification processes (Figure 4). These
293 findings have significant implications for WWTPs accepting young leachate similar to LL3
294 with high NH₄-N concentrations, as co-treatment at recommended VLRs may inhibit
295 nitrification processes, as demonstrated in the current study. When using a volumetric loading
296 rate of >4% (which corresponded to an initial concentration of approximately over 350 mg
297 NH₄-N L⁻¹ when LL3 was added to wastewater from Sites 1 and 3) nitrification inhibition
298 occurred. It was not possible to determine an appropriate NH₄-N based leachate loading

299 recommendation. However, a loading rate of 2% (approximately 90% of total WWTP NH₄-N
300 load) may be more appropriate for the young leachate. This could vary between leachates
301 depending on NH₄-N concentration and presence of other inhibitory compounds which were
302 not observed in levels likely to cause nitrification in this study (Table 4). The results of the
303 beaker experiment were generally in agreement with the results from the site monitoring
304 conducted during the current study (Figure 2) and previous studies (Kalka, 2012; Ye et al.,
305 2014). These results demonstrate that hydraulic loading-based acceptance criteria
306 recommendations are not appropriate when co-treating leachate with municipal wastewater,
307 unless leachate NH₄-N composition is considered and known in advance of acceptance.

308

309 Addition of intermediate and young leachate to wastewater MLSS in beaker experiments
310 increased initial NH₄-N concentrations compared to the control. Addition of leachate to
311 wastewater MLSS was observed to increase initial alkalinity concentrations (t=0.125 h)
312 compared to the control, but these increases were not statistically significant. Addition of
313 intermediate age leachate had no impact on final alkalinity (t=48 hr), but young leachate
314 added at all rates examined, significantly increased alkalinity compared to the control
315 ($p<0.05$). Alkalinity was observed to decrease steadily in all beakers, reaching a plateau at
316 approximately 6 hr. This indicates most of the nitrification occurred within the first 6 hours of
317 the batch experiment.

318

319 Effluent NO₃-N concentrations indicate that nitrification occurred in all beakers (Figure 3)
320 with the exception of leachate from Site 1 co-treated with wastewater from Site 1 and young
321 leachate co-treated with wastewater from Site 1 and 3 when added at 10% ($p<0.05$). It is
322 likely that insufficient alkalinity in the wastewater collected from Site 1 caused nitrification
323 inhibition, as there was insufficient alkalinity present to ensure that complete nitrification

324 occurred (Tchobanoglous et al., 2004). Inhibition in young leachate (10%) treatments for
325 both wastewaters was likely caused by leachate toxicity, as alkalinity was not depleted
326 entirely. In a subsequent experiment (unpublished data), leachate was pre-treated with ferric
327 chloride (FeCl_3) and decanted before being co-treated with wastewater from Site 3 at 4% in a
328 beaker experiment. Coagulation did not have any impact on initial $\text{NH}_4\text{-N}$ concentration;
329 however, 48 hr $\text{NH}_4\text{-N}$ concentration was lower than untreated leachate ($p < 0.05$), indicating
330 that coagulation in WWTPs could result in a decrease in ammonium concentration in
331 effluent. It was not possible to determine the cause of this decrease in toxicity; however, this
332 indicates that $\text{NH}_4\text{-N}$ toxicity alone was not the cause. These results indicate the need for site-
333 specific nitrification trials to be conducted when assessing the potential impact of leachate
334 acceptance, especially for young leachate.

335

336 **Conclusions**

337

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

- 345 1. Leachate loading regimes examined were found to be appropriate for effective
346 treatment of intermediate age landfill leachate in the WWTPs examined, but co-
347 treatment may not be suitable in WWTPs with low $\text{NH}_4\text{-N}$ and TN ELVs.

- 348 2. Intermediate leachate, loaded at volumetric ratios of up to 4% or 50% of total
349 WWTP NH₄-N loading, did not significantly inhibit nitrification processes.
- 350 3. Young leachate, loaded at volumetric ratios greater than 2% or approximately
351 90% of WWTP NH₄-N load, resulted in a significant decrease in nitrification.
- 352 4. Hydraulic loading-based acceptance criteria recommendations are not appropriate
353 when co-treating young leachate with municipal wastewater, unless leachate NH₄-
354 N composition is considered and known in advance of acceptance. Site-specific
355 inhibition experiments may be necessary to determine appropriate loading rates.
- 356 5. Nitrogen loading should be considered when estimating the cost of leachate
357 treatment, as leachate may comprise up to 48% of TN and 32% of NH₄-N loading,
358 accounting for a significant portion of WWTPs aeration requirements.

359

360 **Acknowledgements**

361

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

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

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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 ³ yr ⁻¹	7,302	47,744
Yearly average leachate influent volume as percentage of total effluent	%	1.17	2.3

455 WWTP: wastewater treatment plant; P.E.: population equivalent; LL1 and 2: landfill leachate from sites 1, and 2
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473 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	$\mu\text{s cm}^{-1}$	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

474 BOD₅: 5-day biochemical oxygen demand; COD chemical oxygen demand; Sig.: significance level; letters
 475 denote leachate concentrations which are not significantly different to each other when comparing between
 476 leachates.

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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 ³ d ⁻¹	BOD ₅ (kgd ⁻¹)			COD (kgd ⁻¹)			TIC _f (kgd ⁻¹)			TOC _f (kgd ⁻¹)			TN _f (kgd ⁻¹)			NH ₄ -N (kgd ⁻¹)		
			Inf	Eff	%	Inf	Eff	%	Inf	Eff	%	Inf	Eff	%	Inf	Eff	%	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; NH₄-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

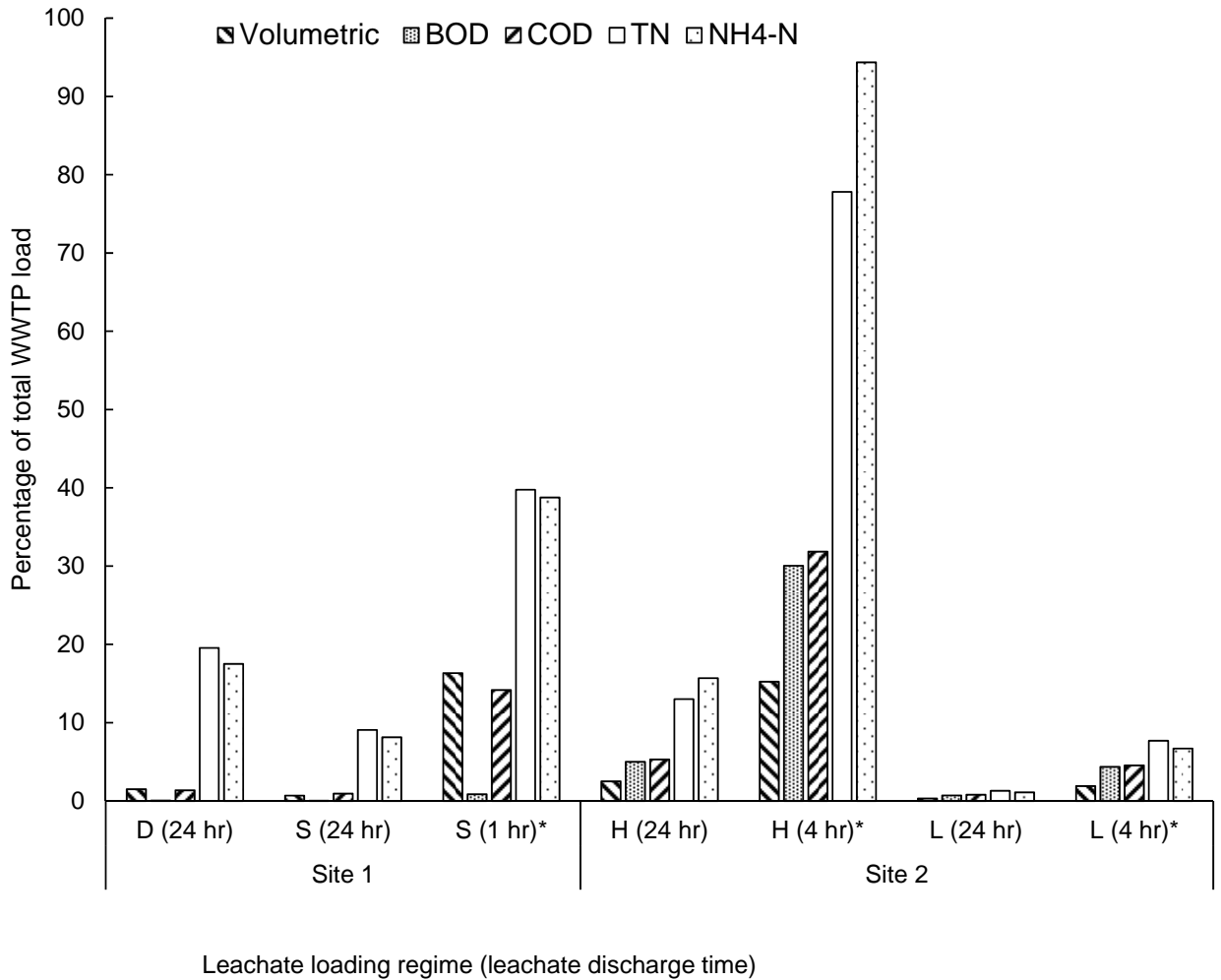
Units: mg L⁻¹; WW: Wastewater; LL: landfill leachate; COD: chemical oxygen demand; NH₄-N: ammonium nitrogen; TON: total oxidized nitrogen (NO₃-N+NO₂-N); MLSS: mixed liquor suspended solids; VSS: volatile suspended solids.

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

	Volume	COD	pH		Dissolved oxygen	
		mg L ⁻¹	pH units		mg L ⁻¹	
		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)

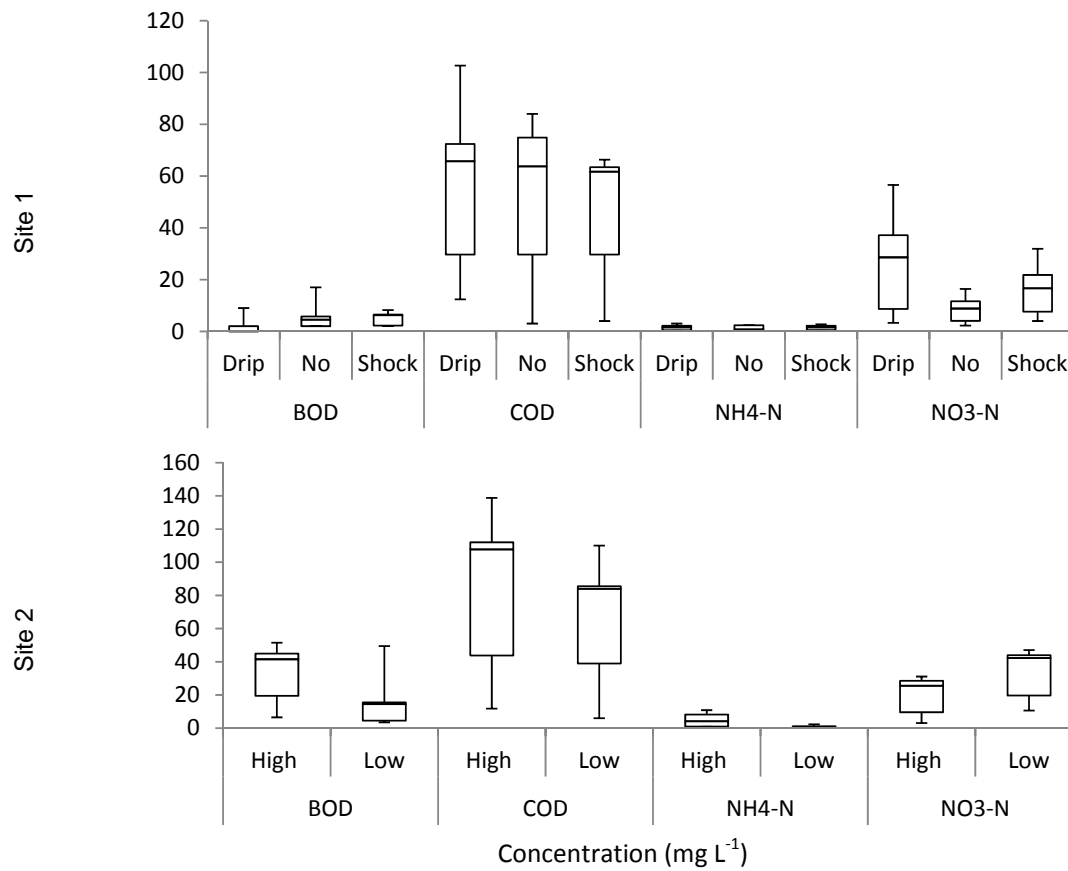
Standard deviation in parenthesis; $p < 0.05$: significance level; *different to control and 0%.

Figure 1 Bar chart showing leachate daily and instantaneous volumetric loading rates (VLR and VLR_i), BOD₅, COD, TN and NH₄-N mass loads as a percentage of WWTP influent mass.



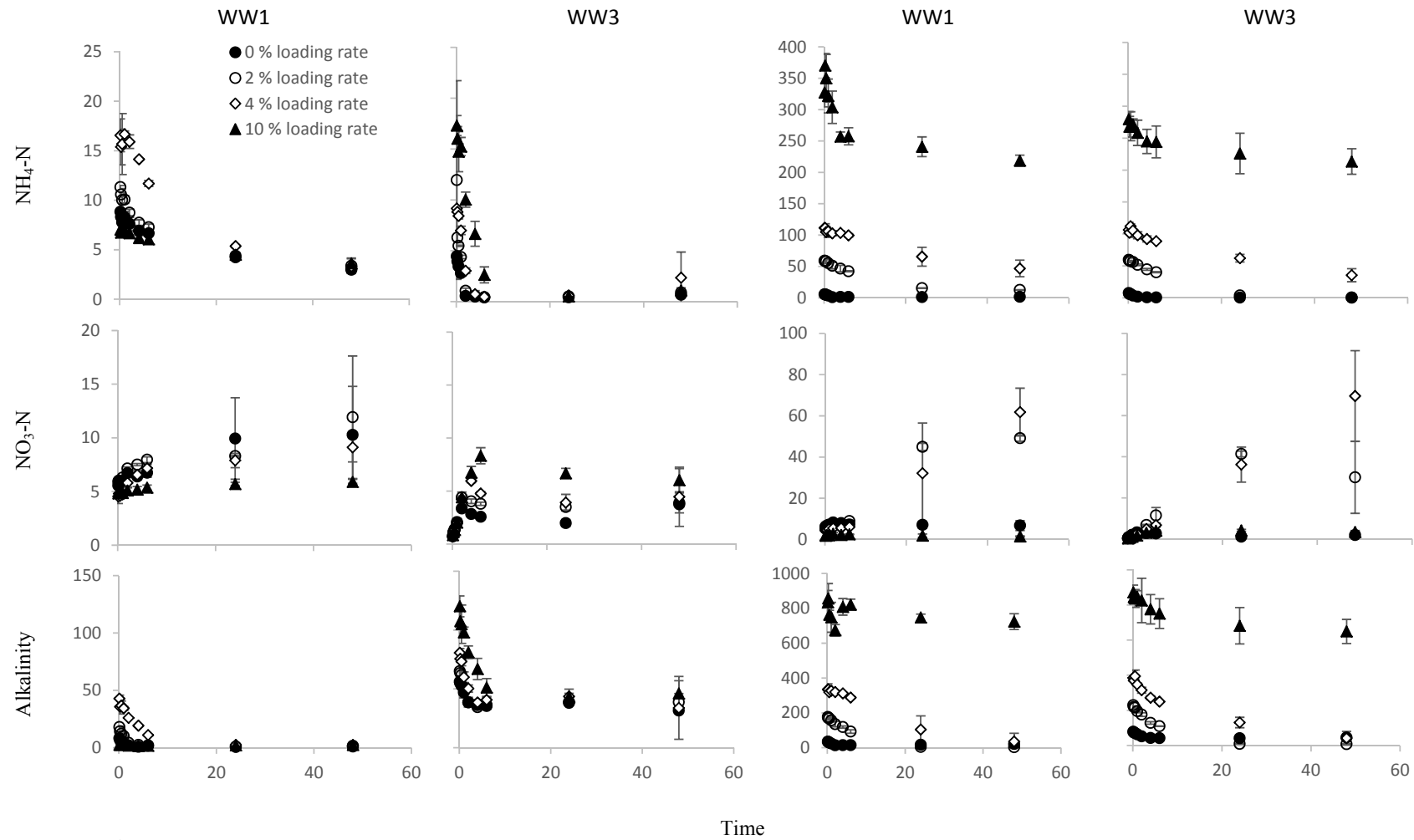
Units: %; D: drip feed; S: shock load; L: low loading; H: high loading; BOD: biochemical oxygen demand; COD: chemical oxygen demand; TN total nitrogen; NH₄-N: ammonium nitrogen; VLR: volumetric loading rate. WWTP: wastewater treatment plant; *denotes VLR_i which is the instantaneous volumetric rate determined 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.



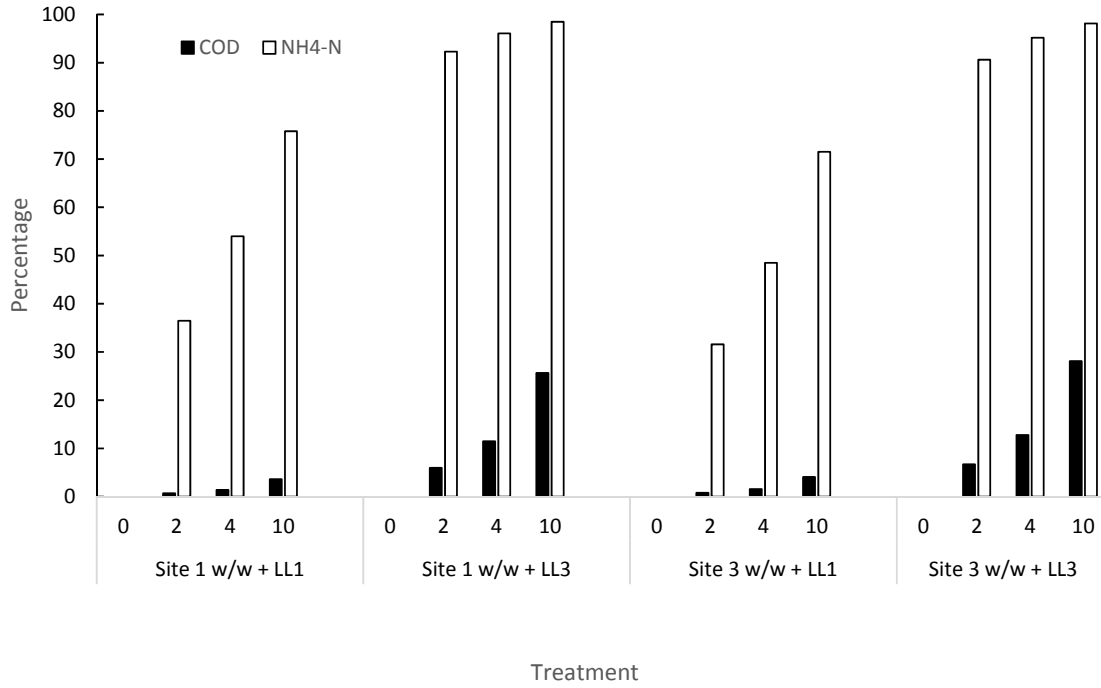
Units: mg L⁻¹; D: drip feed; N: No leachate; S: shock load; L: low loading; H: high loading; BOD: biochemical oxygen demand; COD: chemical oxygen demand; NH₄-N: ammonium nitrogen; nitrate (NO₃-N).

Figure 3 Nitrification inhibition experiment ammonium ($\text{NH}_4\text{-N}$), nitrate ($\text{NO}_3\text{-N}$) and alkalinity trends at 0, 2, 4 and 10% leachate loading rates. Intermediate age leachate



Units: mg L^{-1} ; Error bars denote standard deviation; WW: wastewater; LL: landfill leachate; $\text{NH}_4\text{-N}$: ammonium nitrogen; $\text{NO}_3\text{-N}$: Nitrate nitrogen.

Figure 4 Bar chart showing leachate volumetric loading rate (VLR), COD and NH₄-N mass loads as a percentage of WWTP influent mass for laboratory batch experiments.



Units: %; COD: chemical oxygen demand; NH₄-N: ammonium nitrogen; WWTP: wastewater treatment plant.