Aerobic biological treatment of landfill leachate

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Abstract

There is an ongoing need to treat leachates from landfills using approaches that avoid expensive installation and operating costs. Faced with such a problem, Powys County Council (Wales, UK) developed a treatment system based on practical experience. Leachate was re-circulated through aeration towers containing a biofilm supported on plastic media before being polished in reed/filter beds.

Investigations were undertaken to evaluate the performance of these processes. Replicated model aeration towers (1/300 site scale) were used to establish treatment rates for pollutants in leachates of varying strengths; the effects of temperature and variations in pollutant concentrations were also evaluated. Data from these model experiments were corroborated with findings from pilot-scale plants (1/10 site scale) operating on landfill sites. Assessment of treatment performance was based on the degree of amelioration of standard chemical (ammoniacal-N and total organic carbon) parameters. A range of related parameters including nitrate, pH and redox potential were measured in support of these assessments.

Model system experiments indicated treatment rates at 15 °C (883-1895 mg NH_3-N m^{-3} h^{-1}; 347-1600 mg TOC m^{-3} h^{-1}) that were similar across a wide range of leachate concentrations (37-1880 mgl^{-1} ammoniacal-N; 130-5315 mgl^{-1} COD). Marked changes in the concentration of leachates did not affect treatment efficiency following a short lag effect. Process rates roughly halved with each 5°C decrease in temperature below 15°C, significant nitrification was maintained at temperatures of 0.5-1 °C. High variability in treatment capacity was observed for individual plastic media. Treatment rates in pilot scale plants were slightly higher but broadly consistent with those obtained in model systems.

Keywords: leachate treatment, aerobic, temperature, leachate strength, biofilm.

WIT Transactions on Ecology and the Environment, Vol 92, © 2006 WIT Press
www.witpress.com, ISSN 1743-3541 (on-line)
doi:10.2495/WM060461

1 Introduction

Long-term, cost effective treatment of polluting emissions from landfills is important [1]. As water percolates through wastes emplaced in a landfill it dissolves organic and inorganic components and decomposition products to produce a potentially polluting liquid leachate. It is only relatively recently that the treatment of leachate has started to receive the type of thorough investigation which has been normal practice for sewage and other industrial effluents [2].

The putrescible components in municipal solid waste (MSW) have the potential to generate highly polluting and toxic leachates as they degrade. This degradation progresses through a series of more or less well defined stages towards maturity and eventual stability [3]. Leachate composition varies between stages, being highly enriched with organic breakdown products initially, then acidic with elevated concentrations of metal, chloride, ammonium and phosphate ions [4], then with higher pH and gradually declining concentrations of ammoniacal-N and organic concentrations through the prolonged methanogenic phase. In practice, leachates will be generated by wastes at various stages of degradation on all but the older closed sites. The timescale for each of the degradation stages has been shown to vary considerably according to; the type and nature of the emplaced wastes [5], landfill management practices [6] and local environmental conditions [7].

The composition of aged MSW leachates is such that they may be both polluting [8] and toxic [9] capable of producing severe environmental impacts especially in vulnerable recipients such as aquifers and surface waters. These effects may include eutrophication or toxic effects on aquatic organisms resulting from ammonia, heavy metals or organic compounds. Ammoniacal-N concentrations often present more of a long-term problem, than the leaching of degradable organic substances such as volatile fatty acids [10].

Remediation of leachate has been achieved primarily by aerobic biological treatment [11]. Although these technologies have developed in operational complexity to enhance the rate or extent of the biological conversions taking place [12], the fundamental biological reactions have remained essentially the same [13]. For leachates containing high concentrations of BOD, treatment processes (aerated lagoons, sequencing batch reactors, activated sludge) operating with flocculated heterotrophic micro-organisms in suspension and the assimilation of ammoniacal-N into biomass, have been widely reported [14]. For methanogenic leachates, nitrification utilising autotrophic, fixed microbial film processes (biofilm towers, trickling biofilters, rotating biological contractors) have been shown to be generally effective in reducing ammoniacal-N concentrations [15].

This study examines the effectiveness of a leachate treatment technology developed for former MSW landfill sites managed by Powys CC in Mid Wales, UK. Previous on-site investigations [16] indicated that leachate treatment was achieved primarily within aeration towers, so this treatment stage became the focus of more detailed study using replicated ‘model’ systems and pilot scale systems for on-site validation of findings.

2 Materials and methods

Replicated model systems (1/300 of typical site scale) of aeration towers filled with plastic media (Mass Transfer Cascade Filterpak ™ Stoke, UK) were used to establish treatment rates for leachates of varying strengths (see Figure 1 for schematic) operating under different temperature regimes.

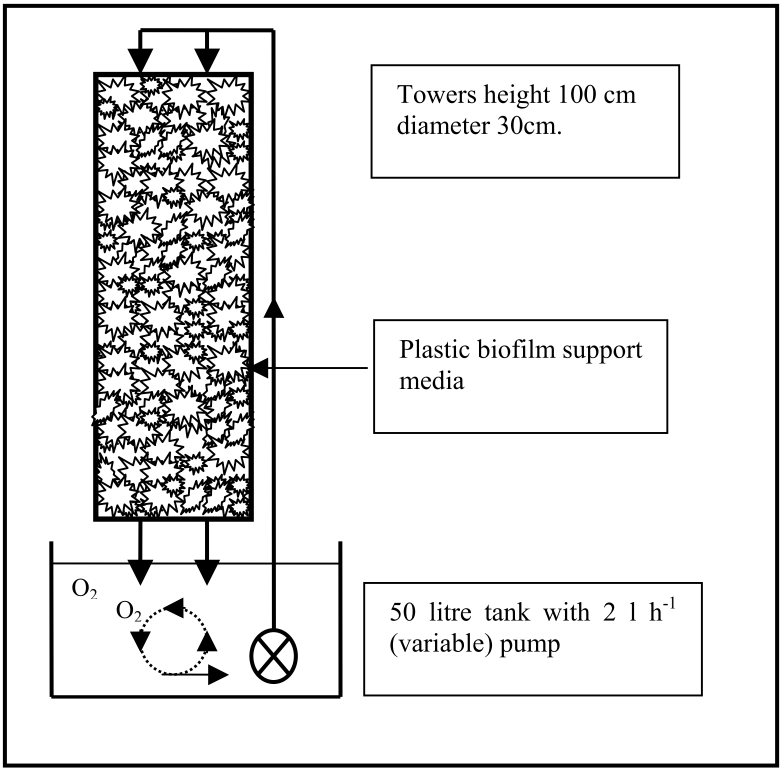

Figure 1: Schematic of model system experimental set-up.

Data reported are for a series of experiments using leachates from three landfill sites with widely varying characteristics (Table 1); Nantycaws 2 and Trecatti were operational. For practical reasons, experiments involved treating leachate in batches to completion. Experiments typically included 3-4 replicates depending on the number of treatment comparisons. Findings from these model experiments were corroborated with data from pilot-scale plants (1/10 of typical site scale).

Leachates were treated in temperature controlled growth rooms (4 replicates) at temperatures of 0.5-1, 10, 15 and 30 °C; the first three temperatures were chosen to represent the predominant range under UK conditions whilst the highest temperature may represent close to 'optimum' conditions for nitrification

[17]. Data presented here are for one site (Borth) only; data comparing treatment rates for different leachates are for Borth, Nantycaws 1 & 2 and Trecatti leachate at 15 °C. Air and leachate temperatures were routinely monitored during pilot plant trials; for the data presented, mean leachate temperatures were 11, 16.5, 13 and 16.1 °C for Borth, Nantycaws 1, Nantycaws 2 and Trecatti respectively. Repeat runs were treated as replicates for the pilot plant.

Table 1: Typical characteristics of landfill leachates included in studies.

Site	pH	NH_4-N mgl^{-1}	Total Fe mgl^{-1}	COD mgl^{-1}	BOD mgl^{-1}
Borth	7.5	177	10.3	137	42
Nantycaws 1	7.7	37	0.5	131	22
Nantycaws 2	8.1	1880	2.1	5315	639
Trecatti	7.9	1195	3.4	1575	124

Treatment rates were routinely recorded following changes in leachate concentration or composition to identify any differences in treatment rate resulting from variations in the prior history of individual model towers. Data are presented for one occasion where intensive monitoring was undertaken. Replicate towers were exposed to full strength (130 mg l^{-1} ammoniacal-N) or fully treated (< 1 mg l^{-1} ammoniacal-N) Borth leachate for several days, then all towers were switched to full strength Borth leachate and changes in ammoniacal-N recorded over the subsequent days treatment completion.

Individual media elements were investigated to determine the degree of heterogeneity in nitrification potentials within the model systems. These were submerged in solutions of 20 mgl^{-1} ammoniacal-N (pH 6.3) and placed on orbital shakers (20 °C). Ammoniacal-N concentrations were measured initially and twice daily until treatment completion.

Ammoniacal-N was determined [18] using a Cecil Series 2 spectrophotometer measuring absorbance at 630 nm. Nitrate was determined by anion exchange chromatography (Dionex QIC Ion Chromatograph); samples were filtered (< 0.2 µm) prior to injection. Total organic carbon was measured using a Shimadzu analyser (TOC-5050). The pH and Eh of samples were determined routinely using Hanna (301) meters. Dissolved oxygen concentrations were recorded using a Jenway (970) oxygen meter.

Treatment rates were determined by fitting linear regressions to changes in concentrations with time for individual replicate towers. Rates were then re-calculated as mg m^{-3} media h^{-1}. Most experiments, involved in excess of 10 sampling occasions with sampling intervals varied according to the period of the experimental run as affected by leachate strength. There was no evidence of these rates being affected by substrate concentrations except when treatment approached completion as illustrated in Figure 2; regression R^2 values were consistently > 90 and usually > 95%. Mean process rates were then compared by one-way analysis of variance.

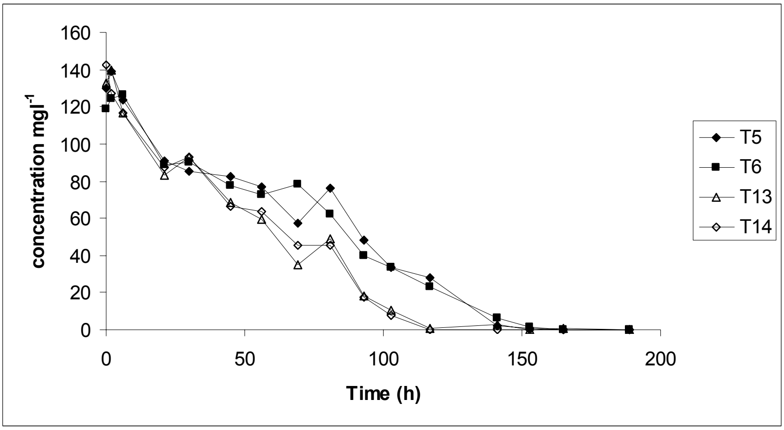

Figure 2: Linear reductions in ammoniacal-N concentration (Borth leachate) for 4 replicate model tower systems.

3 Results

Effects of varying temperature on treatment of the Borth leachate are described in Table 2. Nitrification rates and nitrate-N production rates broadly corresponded when ammonification of organic-N is taken into account. Between 0.5 °C and 15 °C process rates roughly doubled for each 5 °C temperature increment, with rates at 15 °C roughly a third of the optimum 30 °C rates. Significant amelioration of leachate was maintained even at temperatures close to freezing point. For this leachate, pH remained above 7.5 throughout the treatment period; apart from the initial 2 hour period when dissolved oxygen concentrations and redox potentials were low, these parameters stabilised in excess of 7 mg l^{-1} and 170 mV respectively for most of the remaining period.

Table 2: Effects of varying temperature on process rates (mg $m^{-3}h^{-1}$) for Borth leachate; a) ammoniacal-N, b) nitrate-N and c) organic carbon.

a)

Temperature °C	0.5	10	15	30
Mean	200	469	861	3109
Standard deviation	30.3	119.8	133.9	94.7

b)

Temperature °C	0.5	10	15	30
Mean	169	505	765	3353
Standard deviation	42.0	142.8	119.0	236.6

c)

Temperature °C	0.5	10	15	30
Mean	408	1097	1600	4343
Standard deviation	18.9	290	123.5	611.8

Comparisons of process rates for different leachates at 15 °C are presented in Table 3. Ammoniacal-N concentrations decreased more rapidly for the stronger leachates, particularly Nantycaws 2. This difference was not reflected in nitrate production rates. Ammonia volatilisation detected for the Nantycaws 2 leachate could not fully explain this discrepancy; denitrification was detected and this occurrence was consistent with low Eh values (c. 100 mV) for much of the early treatment of this leachate. Organic C treatment rates for the Nantycaws 1 leachate, which had low initial OC, were notably lower than for other leachates. Values for the two operational sites were intermediate and highly variable

Table 3: Process rates at 15 °C constant temperature (mg m^{-3} h^{-1}) for a) ammoniacal-N, b) nitrate-N and c) organic carbon for model systems.

a)

Leachate	Borth	Nantycaws 1	Nantycaws 2	Trecatti
Mean	968	883	1895	1335
Standard deviation	123.5	327.9	242.7	97.7

b)

Leachate	Borth	Nantycaws 1	Nantycaws 2	Trecatti
Mean	861	1191	982	1095
Standard deviation	133.9	266.6	617.1	529.7

c)

Leachate	Borth	Nantycaws 1	Nantycaws 2	Trecatti
Mean	1600	347	1304	1024
Standard deviation	123.5	136.0	635.5	415.8

Table 4: Process rates at variable temperature (mg $m^{-3}h^{-1}$) for a) ammoniacal-N, b) nitrate-N and c) organic carbon for pilot plant systems.

a)

Leachate	Borth	Nantycaws 1	Nantycaws 2	Trecatti
Mean	2428	2184	2333	2181
Standard deviation	4.8	422.7	57.7	508.6

b)

Leachate	Borth	Nantycaws 1	Nantycaws 2	Trecatti
Mean	1636	2651	1656	1050
Standard deviation	221.2	72.7	7.8	378.2

c)

Leachate	Borth	Nantycaws 1	Nantycaws 2	Trecatti
Mean	2582	3404	1254	354
Standard deviation	455.2	1318	619.3	137.7

Batches of leachate were treated in pilot plants on each of the landfill sites (Table 4). In making comparisons between model and pilot plant systems differences in temperature and general environmental conditions must be considered. Rates of ammoniacal-N reduction and nitrate-N production were generally comparable and broadly consistent with data from model systems with the exception of the very high OC values for Nantycaws 1.

Nitrification capacity (Figure 3) was highly variable between individual media and there was some evidence of a trend towards a reduction in this capacity with depth in the model system towers.

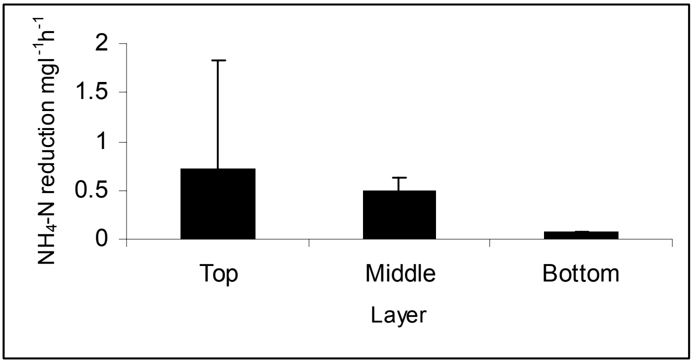

Figure 3: Reductions in ammoniacal-N concentrations for individual media (6 reps) in standard solutions for 3 days (error bars = standard deviations).

Treatment rates were affected (Table 5) by the nature of the preceding leachate to which model systems were exposed. Towers with low strength leachate treated ammoniacal-N at rates about two thirds those of towers treating stronger leachate; this difference was not apparent beyond the first day of the trial.

Table 5: Reduction in ammoniacal-N after 1 and 15 h as affected by previously treated leachate (H = 130 and L = <1 mg l^{-1} ammoniacal-N).

Previous leachate	H	L	H	L
Time (h)	1	1	15	15
Mean mg l^{-1}	9.8	6.3	96.1	66.9
Standard deviation	5.26	5.12	5.70	24.14

5 Discussion

Work undertaken by Tschui *et al.* [19] has shown the specific growth rates of nitrifying bacteria are extremely slow compared with those of heterotrophic bacteria, necessitating the lowering of organic loading rates to reduce the competition between heterotrophic and autotrophic bacteria [20]. Our results indicate that heterotrophic and nitrifying bacteria can co-exist within this treatment system at least across the range of leachates tested.

Nitrification has been demonstrated in soil close to 0 ºC [21]. Kettunen *et al.* [22] have reported ammoniacal-N removal rates of between 65-99% respectively at process residence times of 2.7 and 4.2 days, for aerobic leachate biotreatments at temperatures within the range 1-5 ºC. Nitrification occurs optimally within the range 25-35 ºC [17]. Findings reported here indicate process rates at 0.5 °C 7, 5 and 9% those of optimum values for ammoniacal-N, nitrate-N and organic carbon respectively. In the UK where the majority of leachate production is concentrated during the winter months, data for optimum temperatures are often unrealistically high [11]. Based on laboratory scale experiments the effects of temperature on the rate of nitrification have been estimated at 12% $^{o}C^{-1}$ within the temperature range 7-20 ºC [23]. Our results are again broadly consistent with these general findings.

Nitrification requires a significant amount of oxygen (4.33g O_2 per gram of NH_4-N) [24]. The natural passage of air through voids present in the biofilm support media [25] has been shown to avoid oxygen limitation and in our trials dissolved oxygen concentrations in bulk leachate were maintained close to saturation even for the strongest leachates.

The oxidation of free ammonia to nitrite consumes two moles of alkalinity per mole of ammonia oxidised [26] and may result in acidification. Acidic pH in poorly buffered leachates reduces the concentration of free ammonia and may also inhibit oxidation by reducing the specific growth rate of the bacteria [27]. Although the optimal pH required for nitrification has been estimated at 8.5 [28], our experiments indicate sustained rates of nitrification at pH's < 7.00 although treatment stalling was observed at variable pH's below this value.

It has also been suggested that ammonia may inhibit nitrite oxidation by *Nitrobacter* bacteria. However, more recent studies [27] have however shown that significant variability exists in the degree of inhibition. Ammonia present in high concentrations has also been reported to inhibit its own oxidation by *Nitrosomonas* bacteria but again the degree of inhibition is variable [14] and may be influenced by temperature and pH [29]. There was no evidence of any such inhibition across the range of ammoniacal-N concentrations and pH ranges tested in the trials reported here.

Although there was some evidence of delayed response to marked changes in leachate concentration, the treatment system evaluated proved to be robust both at model and pilot scales across a very wide range of leachate characteristics encompassing long closed to fully operational sites. Clearly there is high spatial and perhaps temporal variability in process capacity within the tower media. Some degree of variability is inevitable but there may be scope for further improvements in treatment rates if some of this variability could be avoided.

Acknowledgements

This work was jointly funded by Biffaward and Biffa Waste.

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