Landfill aeration: review of technical issues and effectiveness

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Introduction

- Studies into landfill aeration since early 1990s, full scale early 2000s:
  - Main players in its development: Germany, Austria, Italy, USA

- What might be the main drivers for landfill aeration in the UK?
  - reduce gas emissions to within the capacity of passive control systems
  - reduce leachate NH$_4$-N to within the capacity of passive control systems
  - currently no strong financial incentive to further reduce GHG emissions

- Content of presentation:
  - what can be achieved under optimized conditions (lysimeters)
  - what has been achieved in full scale projects
  - factors leading to reduced efficiency in full scale projects to date
  - aeration system design
  - fate of leachate nitrogen
  - other aspects e.g. fire/high temperature, settlement, metal mobility
  - challenges, limitations, cost context
Lysimeters* show what is possible:

- Conditions are generally optimized:
  - shredded homogenized waste; no barriers to flow
  - controlled temperature and moisture regime
  - often high aeration rates
  - likely to be good, uniform distribution of air
  - often include high rate leachate recirculation, which aids mixing and liquid/air contact
  - often flushed at high rate
  - easier to do gas and liquid mass balance
  - Typical LSR, 40cm ϕ, 120cm tall, ~70kg/100 litres waste

* Landfill Simulation Reactors, or LSRs
### Lysimeters: results summary

- **Acceleration of carbon flux**
  - mainly as CO₂
  - reductions in solids organic content (RA₄, GP₂₁, BMP, Cellulose, LoI etc.)
- **Rapid removal of leachate NH₄-N to near zero**
- **Some reduction of leachate hard COD**
- **Post aeration: low C-flux, low NH₄-N**
  - fewer data on post-aeration phase emissions

### Table: Lysimeters Results Summary

<table>
<thead>
<tr>
<th>Site/waste details</th>
<th>Aeration/irrigation details</th>
<th>Effects</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Filling period of study zone</strong></td>
<td><strong>Years since closure</strong></td>
<td><strong>Age of waste studied</strong></td>
</tr>
<tr>
<td><strong>Units</strong></td>
<td><strong>Leikam et al, Germany 1997</strong></td>
<td><strong>Klingenthal, Germany</strong></td>
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<td><strong>Leikam et al, Germany 1997</strong></td>
<td><strong>Klingenthal, Germany</strong></td>
<td><strong>Kuhstedt, Germany</strong></td>
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<td><strong>8 - 14 years since closure</strong></td>
<td><strong>6 - 14 years since closure</strong></td>
<td><strong>6 - 14 years since closure</strong></td>
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<td><strong>~100 kgDM</strong></td>
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</tbody>
</table>

| **Temperature** | **Water irrigation rate** | **In situ waste density** | **Diameter of lysimeter** | **Area of lysimeter** |
| **°C** | **l/min** | **kg/m³** | **mm** | **m²** |
| **- 2 to +37** | **23 - 26** | **0.3 (low)** | **400** | **0.126** |
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| **Initial moisture content** | **Initial water density** | **Clean water flushing rate** | **Aeration rate(s)** | **Aeration period** | **Aeration strategy** | **Pre-aeration carbon flux** | **Carbon flux during aeration** | **Carbon flux overall effect** |
| **% WM** | **kg/m³** | **l/min/week** | **l/day** | **d** | **from below** | **m³/t.a** | **m³/t.a** | **%** |
| **23 - 26** | **0.32** | **0.5** | **12** | **10** | **no data** | **2.6 - 34** | **11.6** | **3x acceleration** |
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| **Carbon composition** | **Removal of NH₄-N** | **Impact on metal mobility** |
| **%** | **rate** | **mg/d** | **%** |
| **CO₂** | **No** | **No** | **No** |
| **N₂** | **Yes** | **Yes** | **Yes** |
| **H₂O** | **No** | **No** | **No** |

### Notes
-加速的碳flux，主要为CO₂。
-固体有机物含量的减少（RA₄, GP₂₁, BMP, Cellulose, LoI等）。
-快速去除铵态氮NH₄-N接近零。
-对COD的某些去除。
-后曝气阶段的低C-flux，低NH₄-N。
-很少有关于后曝气阶段的排放数据。
Lysimeters: acceleration of carbon flux

- **Benchmark**
  - Starting point is the gas curve for real landfills:
  - \(\sim 1\text{m}^3/\text{t}.\text{a} \pm /-\), with 50-75 \(\text{m}^3/\text{t}\) potential remaining.
  - Looking for acceleration compared with that.
Lysimeters: acceleration of carbon flux cf anaerobic

- aerobic 3-5x anaerobic
- sometimes get initial burst then slows down
- still significant rates after prolonged aeration period

Sources shown: Brandstatter, Heferlbach lysimeters (2015); Huber-Humer et al, Mannersdorf lysimeters, 2013
### Lysimeters: acceleration of carbon flux

- Table shows carbon flux in a range of aerated lysimeters
- Shown as equivalent LFG flow (50% CH₄ / 50% CO₂) in m³/t.a
- Compare with ‘tail’ rates of 1 m³/t.a:

<table>
<thead>
<tr>
<th>Lysimeter Type</th>
<th>Rate</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Various lysimeters</td>
<td>2.6 - 34</td>
<td>Leikam et al, 1997</td>
</tr>
<tr>
<td>Initial rate, Days 1-40</td>
<td>41</td>
<td>Ritzkowski et al, 2003</td>
</tr>
<tr>
<td>Steady rate, Day 40-250</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>Aerated, wet</td>
<td>22.5</td>
<td>Brandstatter et al</td>
</tr>
<tr>
<td>Aerated, dry</td>
<td>22.5</td>
<td></td>
</tr>
<tr>
<td>Anaerobic control</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>Aerated, wet</td>
<td>11.6</td>
<td>Prantl et al, 2005</td>
</tr>
<tr>
<td>Aerated, wet</td>
<td>10.6</td>
<td>Hrad et al, 2013</td>
</tr>
<tr>
<td>Average over whole study</td>
<td>18.2</td>
<td>Huber-Humer et al, 2013</td>
</tr>
<tr>
<td>Rate at end of study</td>
<td>7.3</td>
<td></td>
</tr>
</tbody>
</table>
Lysimeters: removal of ammonia from leachate

- Examples shown from two studies
- Rapid removal cf flushed anaerobic LSRs
- Range 2.7 – 25 mgNH₄-N/l.d
- Short lag period 35-45 days
- Late appearance of nitrate

Sources: 2003 Ritzkowski et al; 2003 Hantsch et al; 2015 Brandstatter et al
Lysimeters: impact on leachate hard COD

- graph shows aerated cf. anaerobic
- table shows aerated wet/dry cf anaerobic wet
- modest reductions in COD or TOC
- not solely due to flushing

Source: 2011 #751, Fig 3. Kuhstedt lysimeters

Source: 2015 Brandstatter, Heferibach lysimeters

<table>
<thead>
<tr>
<th></th>
<th>AW start</th>
<th>AD start</th>
<th>AN start</th>
<th>AW finish</th>
<th>AD finish</th>
<th>AN finish</th>
</tr>
</thead>
<tbody>
<tr>
<td>COD, mg/l</td>
<td>342</td>
<td>384</td>
<td>399</td>
<td><strong>14.4</strong></td>
<td>58.6</td>
<td>112</td>
</tr>
<tr>
<td>BOD, mg/l</td>
<td>195</td>
<td>225</td>
<td>229</td>
<td>1.2</td>
<td>2.4</td>
<td>37.5</td>
</tr>
</tbody>
</table>

AW & AD = aerated wet/dry; AN = anaerobic, wet
‘Wet’ vs ‘dry’ operation

- Comparison of ‘wet’ (upper chart) and ‘dry’ (lower chart) lysimeters at Kuhstedt
- ‘Wet’: recirculation HRT ~1 week; clean water HRT ~27 weeks;
- ‘Dry’: HRTs ~13 weeks & 450 wks resp.
- NH$_4$-N removed in Dry LSR but at a slower rate (~900d vs ~120d)
- possible role of irrigation/recirculation at full scale
  - similar effect in Austrian lysimeters (Brandstatter et al)

Source: Ritzkowski et al, Sardinia 2003 #056 Figs 2 and 3
Lysimeters: behaviour post-aeration

- Gradual return of some NH$_4$-N but only to still quite low concentrations
- No change in COD
- No CH$_4$ detected in Hrad et al. up to 75 weeks post-aeration
- No longer term post-aeration data found

"Anaerobic" = formerly aerated lysimeter; "Aerobic" = formerly anaerobic lysimeter

Source: WM 2013 Hrad et al. “Anaerobic” = formerly aerated lysimeter; “Aerobic” = formerly anaerobic lysimeter
Field scale studies: basic operational features

- Mostly done at landfills <20m deep
- Areas from 1 to 6ha
- Years since closure: 4 to 39
- Reported data periods mostly <2 years
  - range ~1yr to ~6 yrs
Field scale studies: aeration rates

- Well spacings typically from 10m to 50m

- Aeration rates much lower than in lysimeters
  - often only ~10-20%

- But still high cf normal rates of LFG generation
Field scale results: biochemistry

- Rapid change in biochemistry (1-2 weeks) evident from gas composition
  - Change to $\text{CO}_2 \gg \text{CH}_4$
  - Continued presence of some methane indicates anaerobic zones remain

Source: Cossu et al 2007

Shows rapid change to CO2 > CH4
Field scale results: carbon flux

- Acceleration of carbon release as gas
  - significant cf ‘tail’ rate of 1m³/t.a
  - slower by ~5 to 10x cf lysimeters

Source: Brandstatter et al 2016, Heferlbach, Austria
Shows carbon release as % waste TOC content in full scale (‘Deponie’) and two LSRs, wet and dry (‘Labor’).
Field scale results: leachate NH$_4$-N

- NH$_4$-N removal from leachate achieved only occasionally, and incomplete
- Examples show one that worked, one that did not


Source: Hrad et al. 2015 #200, Mannersdorf, Austria. Aerated at 20-30 m$^3$/t.a
Field scale results: post-aeration

- Few post-aeration data
  - rapid reversion to $\text{CH}_4 > \text{CO}_2$
  - oxygen remains $> 0$

Mean in situ gas composition following cessation of aeration in June 2007

Source: Oncu et al, Sardinia 2013, Fig 4
Factors affecting performance at full scale

- Why full scale systems may perform worse than lysimeters
  - Aeration rates generally much lower
  - Well spacing and well-field design highly variable
  - Air distribution uneven, localised
  - Limited control of moisture regime: zones may be too wet or too dry:
    - *lysimeters often irrigated at high rates by recirculation + flushing*
  - High leachate levels
  - Heterogeneity of the wastes and barriers to flow
    - *e.g. cover, low K wastes, leachate lenses*
    - *preferential flow paths, leakage of air through surface and side slopes*
    - *continued presence of anaerobic zones and anaerobic processes*
  - No control of temperature: e.g. very high T may inhibit nitrifiers
Aeration systems: huge variations in conceptual design

Source: Ritzkowski and Stegmann, 2012

Source: Raga et al, Legnano, Italy

Source: Oncu et al, 2011, Konstanz-Dorfweiher, Germany

Source: Ritzkowski and Stegmann, 2012
Aeration systems and effectiveness

- Aeration pilot studies by University of Padua
  - injection wells at e.g. ~20m spacing
  - monitoring wells at three depths
  - varied injection flow/pressure
  - determine radius of influence

Source: Italy, Cestaro et al, 2003 #571, Fig 2
Aeration systems and effectiveness

- Aeration pilot studies by University of Padua, example of results:
  - wide variation in flow vs pressure relationships over short distances
  - O₂ distribution shows clear evidence of short-circuiting
  - radius of influence range from 20m at Q=50m³/h to 10-15m at Q= 160-230m³/h

Source: Italy, Cossu et al, 2009 #699, Fig 3,
Flow-pressure relationships for different wells

Source: Italy, Cossu et al, 2009 #699, Fig 4,
O₂ distribution at 11mbg when aerating through A3
Aeration systems and effectiveness

- distribution of injected air, from detailed monitoring study
- average waste depth 8-10m
- large areas unreached by aeration at ~22 and 65 m³/t.a via wells at ~25m spacing

Source: Austria, Hrad et al 2013, Mannersdorf, 13 years post-closure. Shows boundary of O2 > 5%; waste 8-10m deep average, range 3-18m.
Air distribution – Timo Heimovaara modelling

- Waste 15m deep
- 0.5m leachate
- Wells to 2m above base
- Wells 30m apart
- Injection +30mb
- Extraction -60mb
- Trade-off: well-spacing vs ΔP (=energy cost)

Sources: Sardinia 2015 #578 Heimovaara et al.
Heimovaara presentation to LANDSS Forum June 2016
Fate of Nitrogen during aeration: mass balance

- Quantification of NH$_3$, N$_2$O and N$_2$ in off gases; NH$_4$-N and TON in leachate phase
- Evidence that both nitrification and denitrification occur
- Austrian lysimeters: shows % of initial total N content, T$_{N_{\text{init}}}$, after 2+ years aeration
- Overall: ‘Dry’ N mobilisation similar to ‘Wet’ but gaseous loss smaller and greater % as nitrate

Aerated wet: total N 'loss'/mobilisation = 24.6% of waste T$_{\text{init}}$

- Denitite to N2
- N2O in gas
- NH3 in gas
- Leachate NH4-N
- Leachate NO3-N

Aerated dry: total N 'loss'/mobilisation = 25.9% of waste T$_{\text{init}}$

- Denitite to N2
- N2O in gas
- NH3 in gas
- Leachate NH4-N
- Leachate NO3-N

Other issues: temperature

Kuhstedt, 14 years post-closure: temperature peaked during second year of aeration, then steady decline from \( \sim 50^\circ \text{C} \) to \( \sim 30^\circ \text{C} \) over the next 3 years.

Milmersdorf, 4 years post-closure: temperatures reached \( > 60^\circ \text{C} \) within one year of aeration.
Other issues: accelerated settlement

- **Campodarsego data:**

- **Kuhstedt data:**

Source: Ritzkowski et al 2003 #570, Fig5 
~10m waste; 14+ years since closure.

Source: Gisbert 2010, Kuhstedt data

Source WM 2014 Fig 6. Settlement measurements at six locations
12m waste; 22 years since closure

Source: Gisbert 2010, Kuhstedt data
Challenge for in situ aeration

- Get sufficient air to a high % of the waste mass
  - combination of deep and shallow wells?
  - use closer well spacing?
  - use higher pressures?
  - aim for the most cost-effective combination of well field design, well spacing and blower sizing
- Create optimum moisture regime for nitrification and especially for denitrification
  - possible need for leachate recirculation
  - how to achieve optimum moisture in unlined landfills
- Mass balance monitoring to improve understanding of N removal mechanisms
- Quantify cost/benefit elements
  - Capex: wells, blowers, pipework, control systems, off-gas treatment
  - Opex: power, staffing, loss of gas revenue, etc
  - Reduced gas and leachate management costs; subsidies/incentives