Evaluation of Leachate Recirculation on Nitrous Oxide Production in the Likang Landfill, China
Chun Man Lee, Xue Rui Lin, Chong Yu Lan, Samuel Chun Lap Lo, and Gilbert Yuk Sing Chan*

ABSTRACT
Landfill leachate recirculation is efficient in reducing the leachate quantity handled by a leachate treatment plant. However, after land application of leachate, nitrification and denitrification of the ammoniacal N becomes possible and the greenhouse gas nitrous oxide (N₂O) is produced. Lack of information on the effects of leachate recirculation on N₂O production led to a field study being conducted in the Likang Landfill (Guangzhou, China) where leachate recirculation had been practiced for 8 yr. Monthly productions and fluxes of N₂O from leachate and soil were studied from June to November 2000. Environmental and chemical factors regulating N₂O production were also accessed. An impermeable top liner was not used at this site; municipal solid waste was simply covered by inert soil and compacted by bulldozers. A high N₂O emission rate (113 mg m⁻² h⁻¹) was detected from a leachate pond purposely formed on topsoil within the landfill boundary after leachate irrigation. A high N₂O level (1.09 µg L⁻¹) was detected in a gas sample emitted from topsoil 1 m from the leachate pond. Nitrous oxide production from denitrification in leachate-contaminated soil was at least 20 times higher than that from nitrification based on laboratory incubation studies. The N₂O levels emitted from leachate ponds were compared with figures reported for different ecosystems and showed that the results of the present study were 68.7 to 88.6 times higher. Leachate recirculation can be a cost-effective operation in reducing the volume of leachate to be treated in landfill. However, to reduce N₂O flux, leachate should be applied to under-ground soil rather than being irrigated and allowed to flow on topsoil.

Nitrous oxide is an important infrared-absorbing trace gas that contributes 5 to 6% of the anthropogenic forcing of the global energy balance. Because of its persistent half-life of 150 yr in the atmosphere (Hao et al., 1987), it can be transported to the stratosphere where it is photochemically oxidized to NO and responsible for O₃ depletion (Rodhe, 1990). Although the concentration of the N₂O in ambient air is about 1000 times less than that of CO₂ (Watson et al., 1992), it is about 200 times stronger than that of CO₂ in terms of radioactive forcing. Since pre-industrial times, the atmospheric concentration of N₂O has increased from about 270 µg L⁻¹ to a recent measure of 315 µg L⁻¹ (Department of the Environment, Transport and the Regions, 1998; Leuenberger and Siegenthaler, 1992). Soils and oceans are the primary natural sources of N₂O (Seiler and Conard, 1987). The planetary sum of N₂O sources was estimated to be about 15 Tg N yr⁻¹, of which more than one-half results from soil microbial activity (McElroy and Wofsy, 1986; Davidson, 1991).

In developing countries such as China, urban refuse disposal is often in open dumps, and in most cases the N₂O produced is released into the atmosphere. Composting and landfilling operations have been identified as possible significant sources of N₂O (Christensen et al., 1996; Rettenberger and Schreier, 1996). Borjesson and Svensson (1997) conducted a study on three Swedish landfill sites where soil N₂O levels reached more than 18 000 mg L⁻¹ in a landfill covered with pure sewage sludge. However, there are no reported studies on the fluxes of N₂O due to storage and recirculation of landfill leachate.

In landfill topsoil where oxygen is readily available from ambient air, irrigation or flowing of leachate, having a high level of ammoniacal N, is expected to result in high levels of N₂O production from ammonium oxidation or nitrate reduction. According to Ludvigsen et al. (1998), denitrification was the main process responsible for the production of 0.3 to 57 mol N₂O d⁻¹ kg⁻¹ (dry wt.) of soil from an anaerobic aquifer contaminated with landfill leachate. The rates of denitrification and nitrification can be affected by a number of factors, such as temperature, oxygen availability, soil moisture content, soil pH, soil total organic carbon, and nitrogen contents. However, there is a lack of information concerning N₂O flux in relation to leachate recirculation practice. In the present study, N₂O flux from Likang Landfill, Guangzhou, China, which practiced leachate recirculation for 8 yr, was monitored monthly from June to November 2000. The contributions of nitrification and denitrification to N₂O production were determined by laboratory incubation studies. The relationships between climatic factors and physico–chemical properties of landfill topsoil and leachate to N₂O production were determined.

MATERIALS AND METHODS

Study Site
Likang Landfill is one of only two ongoing landfill sites in Guangzhou, China. The site has been used for waste disposal since 1992. It is surrounded by hills, except on the northeast side. The landfill consists of an area of about 32 ha and 2 870 000 m³ capacity. Recent daily loadings of municipal solid waste have been 1400 to 1700 Mg (Zhou et al., 1999). Waste is spread in compacted layers with a bulldozer without regard for bulk density or percent saturation. The waste is covered with soil to reduce odor, prevent waste from blowing away, and prevent animals such as dogs from carrying waste from the site. Triplicate covering topsoil samples were collected in terms of distance from the leachate pond boundary (1 and 10 m) for chemical analysis and laboratory incubations. Synthetic

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impermeable top liners were not used in this site for landfill gas emission control.

To reduce loading to the leachate treatment plant, leachate rich in ammoniacal N from a collection pond at the lower site level was pumped via surface pipes at a rate of 400 m$^3$ h$^{-1}$ and discharged onto the topsoil at the southern and uppermost level of the site. Leachate was then allowed to flow by gravity as surface runoff (Fig. 1). Under this leachate recirculation practice, leachate ponds of various sizes (2–105 m$^2$) were formed in the uneven contour of the site.

**Site Measurement**

The humidity and temperature of ambient air at the field site were measured by a wet-bulb hydrometer (Model DO706585; YSI, Yellow Springs, OH). To study the profile and cause of N$_2$O elevation in ambient air, gas samples were collected in triplicate in 10-mL glass pre-evacuated tubes 1.5 m above ground at four locations: 1 m away from the leachate collection pond at the lower site level and 1, 10, and 150 m from a leachate pond of 27 to 105 m$^2$ in size formed after leachate recirculation. The in situ dissolved oxygen level and temperature of leachate samples were measured by an oxygen probe of a dissolved oxygen meter (Model 54ARC; YSI).

To determine the dissolved N$_2$O level in leachate, a 50-mL sample was collected in triplicate from the same leachate pond with a 100-mL syringe. An equal volume of headspace was filled by ambient air and shaken vigorously for 10 min. The volume expanded in the headspace after degassing was recorded and a 10-mL gas sample was collected from the headspace via a three-way valve with a 10-mL pre-evacuated sampling tube. All gas samples were stored in the dark before N$_2$O quantification in the laboratory.

Gas bubbles were observed continuously escaping from the pond. To estimate gas emission rate and N$_2$O level in the bubbles, gas samples were collected by a 225-cm$^3$ sampler modified from a plastic vial. The sampler was immersed into the leachate, fully filled with leachate, and then inverted (up-side down) so that gas bubbles were trapped. A three-way valve was connected to the bottom of the sampler and gas samples were collected by suction and passed to a 10-mL pre-evacuated sampling tube. Plastic tubing was connected between a landfill gas analyzer (Model LFG10-15597; ADC, Leesburg, VA) and the sampler output; the methane and carbon dioxide contents in gas samples were thus determined. The time required to fill the whole sampler was recorded and the gas emission rate from the pond in the form of bubbles was estimated.

Topsoil on the field site was highly contaminated by leachate, especially in the zones where fresh leachate was continuously flowing through. Nitrous oxide flux from leachate-contaminated topsoil was determined by collecting gas samples 1 and 2 m away from the leachate pond. Holes of 1 cm in diameter and 10 cm in depth were made by inserting an iron pipe into the soil at distances 1 and 2 m from the leachate pond boundary. Plastic boxes were inserted in triplicate into the soil at each distance and equilibrated for at least 0.5 h. Gas samples were collected with 10-mL pre-evacuated sampling tubes. Temperature of landfill topsoil was measured by inserting a thermometer to a 5-cm depth. The soil moisture content was the total weight loss of a soil sample after it has been dried at 105°C until a constant weight was obtained (Allen, 1989).

**Physico–Chemical Analysis**

Extractable soil NH$_4$–N, NO$_3$–N, and NO$_2$–N were determined by shaking 10-g soil samples in 100 mL 2 M KCl solution. ammoniacal N was determined by the Indophenol-blue method (Allen, 1989), while NO$_3$–N and NO$_2$–N were determined with ion selective probes (Models 9307BN and C9346BN, respectively; Orion, Beverly, MA). Soil pH was determined from suspensions of air-dried soil in deionized water by an ISE meter (Model 720A, Orion). Total organic matter was determined by the loss in weight after igniting at 450°C for 16 h (Allen, 1989). Inorganic N sources in leachate were also measured by the same methods described above while the extraction step was omitted and dilution factors were applied if necessary.

**Laboratory Incubations**

**Nitrification and Denitrification Nitrous Oxide Production**

An incubation study was conducted to study the proportion of N$_2$O produced in a landfill of leachate-contaminated soil due to autotrophic nitrification and denitrification. Soil samples were taken in triplicate at depths of 2 to 7 cm, at 1 and 10 m away from the leachate pond boundary. All soil samples were chilled at their field moisture condition and brought back to the laboratory and stored at 4°C. All incubations were completed within 5 d. Triplicate 10-g samples were incubated at 25°C in 50-mL serum bottles under four different conditions: (i) ambient air; (ii) 10 Pa of C$_2$H$_2$ (5 mL of 0.1% C$_2$H$_2$ per bottle) to inhibit autotrophic nitrification (Berg et al., 1982); (iii) 10 kPa of C$_2$H$_2$ (5 mL of 100% C$_2$H$_2$ per bottle) to inhibit denitrification N$_2$O reduction (Ambus, 1998); and (iv) pure N$_2$ (flushing with N$_2$ for 3 min) to simulate an anaerobic envi-
Nitrification and Denitrification Potential Assays

Since N\textsubscript{2}O can be produced by both nitrifiers and denitrifiers, the potential for N\textsubscript{2}O production in landfill soils under natural conditions is related to the rates and extent of nitrification and denitrification. Thus, nitrification potential assay was conducted to estimate the activity of the nitrifier population in the soil, which is basically a static analysis (Schmidt and Belsky, 1982). Triplicate 20-g samples of field-moist soil were mixed with 100 mL substrate (1 mM phosphate buffer, pH 7.1–7.4 and 50 mg NH\textsubscript{4}Cl L\textsuperscript{-1}) in 500-mL wide-mouth Erlenmeyer flasks and incubated at 25°C in the dark until quantitative analysis. Nitrous oxide contents were determined after 0, 30, and 60 min. The nitrification potential was determined as the amount of N\textsubscript{2}O produced kg\textsuperscript{-1} soil h\textsuperscript{-1}.

Gas Chromatography

All gas samples collected in the pre-evacuated tubes from the landfill and incubation studies were kept at 4°C and in the dark until quantitative analysis. Nitrous oxide contents were determined after injecting a 1-mL gas sample to a gas chromatograph (Model HP 4890; Hewlett-Packard, Wilmington, DE), equipped with Porapak Q column (80/100 mesh; 350 cm in length × 1/8 in. stainless steel; Alltech Associates, Deerfield, IL) (Upstill-Goddard et al., 1996). The column temperature was maintained at 70°C. Nitrogen was used as carrier gas at 15 mL min\textsuperscript{-1} and the temperature for the electron capture detector was set to 350°C. The N\textsubscript{2}O concentration was calculated by comparing the peak areas of N\textsubscript{2}O standards (Model Scotty II, Analyzed Gases 072263; Orion, Deerfield, IL).

Statistics

Differences between treatment groups and control groups were tested by Student’s t test following Bhattacharya and Johnson (1977) and Daniel (1987) and the r values were reported.

RESULTS

Field Study

Climatic information, including topsoil and leachate temperatures (0.5 m from pond surface), are shown in Table 1. The highest ambient temperature of 38°C was detected in September, while the highest pond leachate temperature of 42°C was detected on the sampling day in August. The lowest ambient temperature was re-

### Table 2. Physico-chemical properties of topsoil samples collected near the leachate pond from July to November 2000.

<table>
<thead>
<tr>
<th>Distance (m) from pond</th>
<th>12 July</th>
<th>10 August</th>
<th>11 September</th>
<th>11 October</th>
<th>14 November</th>
</tr>
</thead>
<tbody>
<tr>
<td>NH\textsubscript{4}\textsuperscript{+}-N, mg L\textsuperscript{-1}</td>
<td>33.7 ± 2.63</td>
<td>54.1 ± 1.62</td>
<td>1735.0 ± 18.22</td>
<td>403.0 ± 10.63</td>
<td>55.6 ± 2.66</td>
</tr>
<tr>
<td>NO\textsubscript{2}-N, mg L\textsuperscript{-1}</td>
<td>9.3 ± 1.23</td>
<td>12.0 ± 0.44</td>
<td>31.3 ± 4.21</td>
<td>84.0 ± 6.23</td>
<td>12.0 ± 0.38</td>
</tr>
<tr>
<td>NO\textsubscript{3}-N, mg L\textsuperscript{-1}</td>
<td>4.0 ± 0.22</td>
<td>4.0 ± 0.20</td>
<td>4.5 ± 0.10</td>
<td>5.0 ± 0.23</td>
<td>4.0 ± 2.23</td>
</tr>
<tr>
<td>pH</td>
<td>9.0 ± 0.22*</td>
<td>9.1 ± 0.12*</td>
<td>8.7 ± 0.22*</td>
<td>8.7 ± 0.14*</td>
<td>9.2 ± 0.13*</td>
</tr>
<tr>
<td>Soil moisture content, %</td>
<td>29.0 ± 2.65**</td>
<td>29.1 ± 1.22**</td>
<td>34.1 ± 1.80**</td>
<td>30.9 ± 2.49**</td>
<td>29.4 ± 2.12**</td>
</tr>
<tr>
<td>Total organic carbon, %</td>
<td>ND†</td>
<td>ND</td>
<td>3.2 ± 0.21*</td>
<td>5.4 ± 0.11*</td>
<td>4.6 ± 0.51*</td>
</tr>
</tbody>
</table>

* Significant at the 0.05 probability level (comparison between 1- and 2-m samples).
** Significant at the 0.01 probability level (comparison between 1- and 2-m samples).
† Not determined.
The dissolved oxygen detected in the pond was low, whereas the N₂O contents in leachate samples were high (1353–4220 mg L⁻¹). The physico-chemical parameters of leachate including inorganic N contents and pH are listed in Table 2. The dissolved oxygen detected in the pond was low (0.6–0.7 mg L⁻¹). The concentration of NH₄–N in the leachate samples was high (1353–4220 mg L⁻¹) (Table 2).

Landfill soil samples collected near the leachate pond had a relatively high concentration of NH₄⁺–N (33.7 to 1735 mg kg⁻¹). The soil samples were generally alkaline and the total organic carbon content was about 3 to 14%. Moisture contents of the soil samples collected 1 m from the leachate pond were all significantly higher (P < 0.01) than soil samples collected 2 m from the leachate pond, indicating that the topsoil adjacent to the pond was highly contaminated and flooded with leachate.

The gas bubbled in the leachate pond was mostly landfill gas produced after anaerobic degradation of municipal solid waste, as it generally had a high methane content (12 to 37%) and high CO₂ content (8.5 to 17%) (Table 3). The gas also had a high level of N₂O, 0.73 to 1.56 μg N L⁻¹. The dissolved N₂O in the water sample collected in the leachate pond was 0.35 to 0.80 μg N L⁻¹.

Nitrous oxide emitted from contaminated topsoil near the leachate pond ranged from 0.6 to 1.1 μg L⁻¹ in the period from September to November (Table 4). Production of N₂O in soil samples collected from September to November was not affected by 10 Pa of C₂H₂, indicating that no N₂O was produced by autochthonous nitrification (Table 5). Relative net N₂O production from denitrification ranged from 26.4% to more than 100%.

### Contributions of Nitrification and Denitrification on Nitrous Oxide Production

Production of N₂O in soil samples collected from September to November was not affected by 10 Pa of C₂H₂, indicating that no N₂O was produced by autochthonous nitrification (Table 5). Relative net N₂O production from denitrification ranged from 26.4% to more than 100%.

### Denitrification and Nitrification Potentials

The denitrification potential was observed to be higher at 1 m from the pond than 10 m from the pond, except in the soil samples collected in September (Table 6). There was no consistent relation between nitrification potential and topographic position. The greatest value

### Table 3. Nitrous oxide, CH₄, and CO₂ levels in gas bubbled out from the leachate pond, and dissolved N₂O level in pond water sample from June to November 2000.

<table>
<thead>
<tr>
<th>Date</th>
<th>N₂O, μg N L⁻¹</th>
<th>CH₄ %</th>
<th>CO₂ %</th>
<th>N₂O emission rate, mg N m⁻³ h⁻¹</th>
<th>N₂O emission rate, mg N m⁻³ h⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>18 June</td>
<td>1.6 ± 0.46</td>
<td>37.3</td>
<td>16.5</td>
<td>57.1 ± 16.68</td>
<td>22.8 ± 6.67</td>
</tr>
<tr>
<td>12 July</td>
<td>0.7 ± 0.09</td>
<td>37.0</td>
<td>15.0</td>
<td>21.1 ± 1.74</td>
<td>8.5 ± 0.70</td>
</tr>
<tr>
<td>10 August</td>
<td>0.7 ± 0.05</td>
<td>21.9</td>
<td>10.0</td>
<td>159.8 ± 17.51</td>
<td>51.9 ± 4.68</td>
</tr>
<tr>
<td>11 September</td>
<td>1.1 ± 0.07</td>
<td>19.9</td>
<td>12.3</td>
<td>226.2 ± 14.66</td>
<td>113.1 ± 7.33</td>
</tr>
<tr>
<td>11 October</td>
<td>1.0 ± 0.15</td>
<td>19.9</td>
<td>12.4</td>
<td>289.2 ± 44.32</td>
<td>101.2 ± 15.51</td>
</tr>
<tr>
<td>14 November</td>
<td>0.8 ± 0.06</td>
<td>15.6</td>
<td>9.5</td>
<td>176.6 ± 51.69</td>
<td>81.2 ± 23.77</td>
</tr>
</tbody>
</table>

### Table 4. Nitrous oxide concentration in gas samples emitted from topsoil near the leachate pond from July to November 2000.

<table>
<thead>
<tr>
<th>Date</th>
<th>mg L⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>12 July</td>
<td>1.0 ± 0.10**†</td>
</tr>
<tr>
<td>10 August</td>
<td>1.0 ± 0.10**</td>
</tr>
<tr>
<td>11 September</td>
<td>1.0 ± 0.06**</td>
</tr>
<tr>
<td>11 October</td>
<td>1.0 ± 0.04**</td>
</tr>
<tr>
<td>14 November</td>
<td>0.9 ± 0.28</td>
</tr>
</tbody>
</table>

* Significant at the 0.05 probability level (compared with uncontaminated landfill-covering soil).
** Significant at the 0.01 probability level (compared with uncontaminated landfill-covering soil).
† There is no significant difference (P > 0.05) between the data of 1- and 2-m samples.

### Table 5. Nitrification N₂O production and the relative N₂O production by denitrification in the Likang Landfill site from September to November 2000.

<table>
<thead>
<tr>
<th>Date</th>
<th>Nitrification N₂O production</th>
<th>Denitrification N₂O production</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 m from pond</td>
<td>µg N kg⁻¹ h⁻¹ (% of total N₂O)</td>
<td>% of total denitrification</td>
</tr>
<tr>
<td>11 September</td>
<td>0.2 (35.1)**†</td>
<td>49.3**</td>
</tr>
<tr>
<td>11 October</td>
<td>0.4 (–)</td>
<td>149.2**</td>
</tr>
<tr>
<td>14 November</td>
<td>0.6 (–)</td>
<td>139.7**</td>
</tr>
</tbody>
</table>

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
† For nitrification, significance symbols indicate significant difference between N₂O₉₉₉ and N₂O₉₉₉₉; for denitrification symbols indicate significant difference between N₂O₉₉₉ and N₂O₉₉₉₉.
Table 6. Nitrification and denitrification potentials of the Likang Landfill soil samples from September to November 2000.

<table>
<thead>
<tr>
<th>Sampling date</th>
<th>Nitrification potential</th>
<th>Denitrification potential</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 m from leachate pond boundary</td>
<td>10 m from leachate pond boundary</td>
</tr>
<tr>
<td>11 September</td>
<td>110 ± 10.2†</td>
<td>0 ± 0</td>
</tr>
<tr>
<td>11 October</td>
<td>0 ± 0</td>
<td>0 ± 0</td>
</tr>
<tr>
<td>14 November</td>
<td>0 ± 0</td>
<td>420 ± 80.1</td>
</tr>
</tbody>
</table>

† There is no significant difference (P > 0.05) between 1- and 10-m soil samples for either nitrification or denitrification potentials. There is no significant difference (P > 0.05) between nitrification and denitrification potentials for one particular distance of soil sample.

of denitrification and nitrification potential was observed in the soil samples collected in October (1.35 µg N kg⁻¹ h⁻¹) and November (420 µg N kg⁻¹ h⁻¹), respectively.

DISCUSSION

Field measurements were conducted to quantify N₂O flux from Likang Landfill after leachate recirculation. The relative importance of biological nitrification and denitrification for N₂O production was compared.

The ambient and pond leachate temperatures increased gradually from June 2000, reaching a climax in the summer (ambient 38°C, September; leachate 42°C, August) and then declined. The leachate was probably heated by strong solar irradiation, as it is a subtropical landfill, and also by the landfill gas generated after degradation of waste and bubbled from the pond bottom. Gas samples bubbled from the leachate pond had high N₂O levels, ranging from 0.7 to 1.6 µg N L⁻¹, and exhibited a positive correlation with pond temperature (r = 0.703). A doubling of N₂O emission from nitrogenous soil for each 10°C rise in temperature within the range of 15 to 35°C has been reported (Blackmer et al., 1982). However, in the present study, soil temperature (28 to 37°C) showed a loose negative correlation with the topsoil N₂O emission (r = −0.201). The decline in N₂O emission at temperatures higher than 35°C was probably due to the reduction in autotrophic nitrifier activity. Soil desiccation after solar irradiation might also cause a reduction in the mobility of available nutrients for microbes (Focht and Verstraete, 1977).

Both nitrification and denitrification activities are substrate limited. Therefore, N transformation and N₂O emission are expected to be highly related to soil NH₄ or soil NO₃ levels. Our field survey results indicated a significant correlation between the soil NH₄–N level and concentration of N₂O (0.6 to 1.1 µg L⁻¹) detected in the topsoil gas samples (1 and 2 m away from the leachate pond) (r = 0.820 and 0.739, respectively). Similar correlations between NH₄ levels and N₂O fluxes were reported by Mosier et al. (1982, 1983) in cropped soils and Hutchinson et al. (1993) in fertilized soils. Furthermore, the soil NO₃–N level also had a similar positive correlation with the N₂O concentration in topsoil gas samples collected at 2 m from the leachate pond (r = 0.719). However, a low correlation (r = 0.260) between soil NO₂-N level and N₂O production was noted; leachate in the pond kept wetting the nearby soil and thus supplied an unlimited NO₂-N source for N₂O production.

In this study, the dissolved oxygen content in Likang leachate pond was maintained at a low level of 0.7 to 0.8 mg L⁻¹ (3 to 5 cm from surface), and the N₂O emission rates ranged from 8.45 to 113.11 mg N m⁻² h⁻¹. Under low O₂ conditions, Poth and Focht (1985) suggested that the production of N₂O by NH₄ oxidizers resulted from a reductive process in which the bacteria use NO₂ as an electron acceptor. This mechanism not only allows the organisms to conserve limited O₂ but also avoids the potential for accumulation of toxic levels of NO₂–N. Tortoso and Hutchinson (1990) suggested that the NO to N₂O ratio of nitrification products, which normally ranges between 10 and 20 in fully aerobic environments, decreased along with O₂ partial pressure. Despite the effect on nitrification, O₂ also inhibits denitrifying enzyme activity and represses synthesis of new denitrifying enzymes (Payne, 1973). Soil denitrification rates have been shown to increase with added water or reduced aeration (Ardakani et al., 1977; Bremner and Shaw, 1958).

Landfill topsoil usually has a low O₂ partial pressure if a superior landfill top liner is not provided. To determine the correlation between O₂ partial pressure and N₂O flux, a laboratory test was conducted by incubating soil samples at low O₂ partial pressure. The results indicated that anaerobiosis (pure N₂) increased N₂O production in samples by up to 2.5 orders of magnitude. Since the production of N₂O was mainly derived from denitrification, limiting O₂ increased its rate of production. Moreover, N₂O evolved during NH₃-N oxidation arose from the interactions of hydroxylamine oxidoreductase and nitrate reductase, which was in turn influenced by the conditions of aerobiciosis (Firestone, 1982). Hydroxylamine oxidoreductase forms the presumed intermediate (NOH) or its dimer hyponitrite, which may dismutate chemically under reduced O₂ tensions to N₂O (Nicholas, 1978).

The results of laboratory incubations of leachate-contaminated soil samples indicated that N₂O was mainly produced through the denitrification process, whereas nitrification was less responsible for biological production of the gas; less than 3% of N₂O was produced by nitrification. However, since C₂H₂ was used as an inhibitor for autotrophic nitrification, heterotrophic nitrification might not be completely eliminated in the assay (Anderson et al., 1993). The results were contradictory to some reports on forest ecosystems where nitrification was interpreted as an important source of N₂O (Martikainen and De Boer, 1993; Robertson and Tiedje, 1987; Sitaula and Bakken, 1993). Heterotrophs responsible for denitrification have higher tolerance to ele-
vated temperature (i.e., broad range of 15–75°C), and also tolerate low O₂ tension (Focht and Verstraete, 1977). The continuous supply of organic carbon (energy source for denitrifiers) in the site might increase the proportion of N₂O production noted at the Likang landfill site.

There were significant differences (P < 0.05 or 0.01) between the N₂O levels in air at different distances from the pond (Table 7). The N₂O levels determined were all 0.1 to 1.4 times higher than that in the ambient air outside the landfill site. Borjesson and Svensson (1997) conducted a similar study in Swedish landfill sites, and the maximum N₂O emission rates ranged from 3.9 × 10⁻² to 1.31 g m⁻² d⁻¹ from the landfill cover consisting of pure sewage sludge. Bogner et al. (1999) also conducted temporal studies from July to January which indicated that peak production occurred in August in an Illinois (USA) landfill, reaching an emission rate of 8.55 × 10⁻³ g m⁻² d⁻¹ from the landfill surface. In our case study, Likang Landfill, with the practice of leachate recirculation, showed high emission rates of N₂O ranging from 24.83 to 45.86 × 10⁻³ g m⁻² d⁻¹ from landfill topsoil. Moreover, N₂O produced from leachate pond was about 1.12 to 1.43 times higher than that produced from landfill topsoil (µg N L⁻¹) and the emission rate of N₂O (ng N cm⁻² h⁻¹) from the leachate pond was 61.8 to 79.7 times higher than that detected from different ecosystems (Table 8). Due to the practice of leachate recirculation in Likang landfill, accumulation of leachate on soil would provide abundant inorganic N sources for the nitrifying and denitrifying bacteria. Moreover, leachate covering the topsoil would also decrease the O₂ level in the soil underneath and thus increase the N₂O production through nitrification and denitrification, especially the latter.

**CONCLUSION**

Although leachate recirculation can reduce the cost of running a leachate treatment plant and enhance biodegradation, the free flow and uneven contour of leachate through landfill topsoil forms leachate ponds with extremely low partial pressure of oxygen. Low O₂ conditions in leachate favor N₂O production. To fully benefit from leachate recirculation while avoiding excessive formation of N₂O, which is a greenhouse gas, underground pipes should be installed to evenly distribute leachate and an impermeable top liner should be used to control gas emission.

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