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The effect of aeration position on the spatial distribution and reduction of pollutants in the landfill stabilization process – a pilot scale study

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Abstract

Three pilot-scale simulators with different aeration systems were constructed to explore the effects of aeration position on the reduction of pollutants. The simulator with a bottom aeration system successfully distributed oxygen and efficiently inhibited methane production. A close relationship was found between the oxygen distribution and the removal of pollutants, especially that of nitrogen. The transition between nitrification and denitrification in the longitude direction of the simulator with a bottom aeration system contributed to nitrogen removal in aerobic conditions. This process can be defined as a new path for nitrogen removal in addition to simultaneous nitrification and denitrification. The concentration of NH_4^+-N, total nitrogen and total organic carbon dropped to 3, 78 and 204 mg L^{-1}, respectively, after 312 days of bottom aeration and to 514, 659 and 828 mg L^{-1}, respectively, after 312 days of top aeration. These results indicate that the bottom aeration system was more efficient for reducing pollutants than the top aeration system.

Keywords

Aeration position, spatial distribution, methane inhibition, nitrogen removal, landfill

Introduction

Landfill gas emissions are predicted to last at least three decades after landfill closure, and leachate emissions are predicted to continue for many decades or even centuries (Ritzkowski et al., 2006). Public concerns have been raised regarding the long stabilization process, the serious secondary pollution that results from landfill leachate and the significant amount of greenhouse gases (GHG) that are generated and emitted irregularly from landfills. Therefore, it is necessary to create innovative and efficient methods for landfill management in developing countries.

In situ aeration is one technology that introduces ambient air into MSW landfills to enhance biological processes and to inhibit methane production, which provides a means to decrease leachate pollution loads and accelerate sedimentation. In addition, these processes significantly reduce pollutants that would otherwise accumulate within predominantly anaerobic landfills.

Numerous studies have been performed to compare the pollutant removal efficiency in aerobic and anaerobic landfills (Aziz et al., 2010; Bilgili et al., 2008; Borglin et al., 2004; Erses et al., 2008; Giannis et al., 2008; Matthias et al., 2006). Compared with anaerobic landfills, aerobic landfills have higher levels of organic nitrogen removal efficiency, faster sedimentation rates, higher methane production inhibition efficiencies and considerably lower stabilization times.

Many laboratory studies on aeration intensity have been conducted. Ağdağ and Sponza (2004) reported that aerating one day a week efficiently reduced the chemical oxygen demand (COD) and volatile fatty acid (VFA) concentrations in leachate samples. In addition, aerating for three days a week significantly reduced the quantity and the organic content of the waste. Asakura et al. (2010) indicated that the oxygen ratio could be used as an aeration operation parameter at landfill sites to rapidly stabilize organic matter in leachate. This parameter was used because the total organic carbon (TOC) in the leachate was

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rapidly reduced when the oxygen ratio was high. Sang et al. (2009) studied the effects of intermittent and continuous aeration on accelerative stabilization in a landfill bioreactor. The bioreactor with intermittent aeration resulted in a higher decreasing volume rate than that in the bioreactor with continuous aeration. According to Lee et al. (2002), intermittent injection was less effective than continuous injection for landfill stabilization in active young landfills but more effective in aged landfills.

Nitrogen, especially ammonia nitrogen, has a decisive influence on the after-care period of conventional anaerobic landfills (Heyer et al., 2005; Leikam et al., 1999). Thus, multiple laboratory investigations have been conducted to study ammonia nitrogen removal (Jokela et al., 2002; Long et al., 2008; Onay and Pohland, 1998; Shao et al., 2008). Berge et al. (2006), who studied simultaneous nitrification and denitrification in an aerated bioreactor landfill, showed that simultaneous nitrification and denitrification occur in an aerated environment even when the biodegradable C to N ratio is low. Price et al. (2003) found that nitrate could be converted to a harmless byproduct (nitrogen gas) when a landfill is used as a bioreactor. Long et al. (2009) reported that a combination of facultative anaerobic and aerobic conditions in a hybrid bioreactor landfill was effective for eliminating ammonia from leachates and refuse.

However, there are few studies that address the effects of the aeration position on the removal of pollutants. Furthermore, previous studies have not clarified the spatial distribution of oxygen and pollutants in actual landfills. These spatial distributions are important for understanding the relationships between oxygen distribution and pollutant reduction, particularly nitrogen reduction.

In this study, three pilot-scale simulations were conducted to assess the impacts of aeration systems in the Shanghai Lao Gang Landfill in China. The characteristics of gas and leachate from the three pilot scale simulators are useful for understanding the effects of aeration position on the reduction and spatial distribution of contaminants. An understanding of these characteristics is needed to successfully apply this technology in landfills.

Figure 1. Picture of the three on-site simulators.

Materials and methods

Experimental setup

Three pilot-scale simulators (A, B, and C), 3.0 m in height and 1.3 m in diameter, were constructed with pipes for the aeration system and the sample connection (Figures 1 and 2). Coarse gravel was placed at a height of 0.1 m in the bottom of the simulator to provide drainage. Ambient air was pumped into the landfill through perforated pipes (Figure 3). The rate of pumping air into the simulator was controlled with a mass flow meter. The simulators were operated as indicated below:

A: aeration rate 1 L min^{-1}, aeration position-depth of 0.5 m
B: aeration rate 1 L min^{-1}, aeration position-depth of 2.5 m
C: no air injection (the control).

In this study, an aeration depth of 0.5 m was referred to as the top aeration system, and an aeration depth of 2.5 m was referred to as the bottom aeration system.

All three simulators experienced infiltration of rainwater. Leachate from the simulators was stored in the tank for sampling and analysis and was discharged manually. The three simulators were operated for 312 days to compare the effects of aeration position on pollutant reduction. To investigate the effects of cover soil on aeration conditions and methane emissions, a 10 cm layer of soil was placed on the top of the refuge after 240 days of operation. No cover was placed on top of the refuge before 240 days. The basic characterization data from the cover soil used in this experiment are listed in Table 1 and Figure 4.

Waste material

The refuge used for these experiments originated from an old landfill site, located south-east of Shanghai. The landfilled refuge was subjected to anaerobic biological degradation processes for approximately 4 to 5 years prior to this experiment. Manually mixed refuge was compacted to ensure homogenization and was placed in the simulators. Basic characterization data from the refuge that was used in these experiments are listed in Tables 2 and 3.

Sampling and analysis

Leachates from all simulators and storage tanks were characterized on a bi-weekly basis. Syringes, which were withdrawn to create a negative pressure, were connected to the simulators to collect samples at different depths. The leachate samples were transferred into plastic containers and stored at 4 °C. Prior to anion analysis, all samples were centrifuged and filtered with a 0.45 μm microfiltration membrane. The pH of the leachate was measured with a pH meter (PHS-3C, China), and the TOC and total nitrogen (TN) were measured with a TOC analyzer (Shimadzu Inc., Japan). The ammonia nitrogen (NH_4^+-N) levels, the water content, and the loss by ignition were determined by using the standard methods proposed by the China EPA

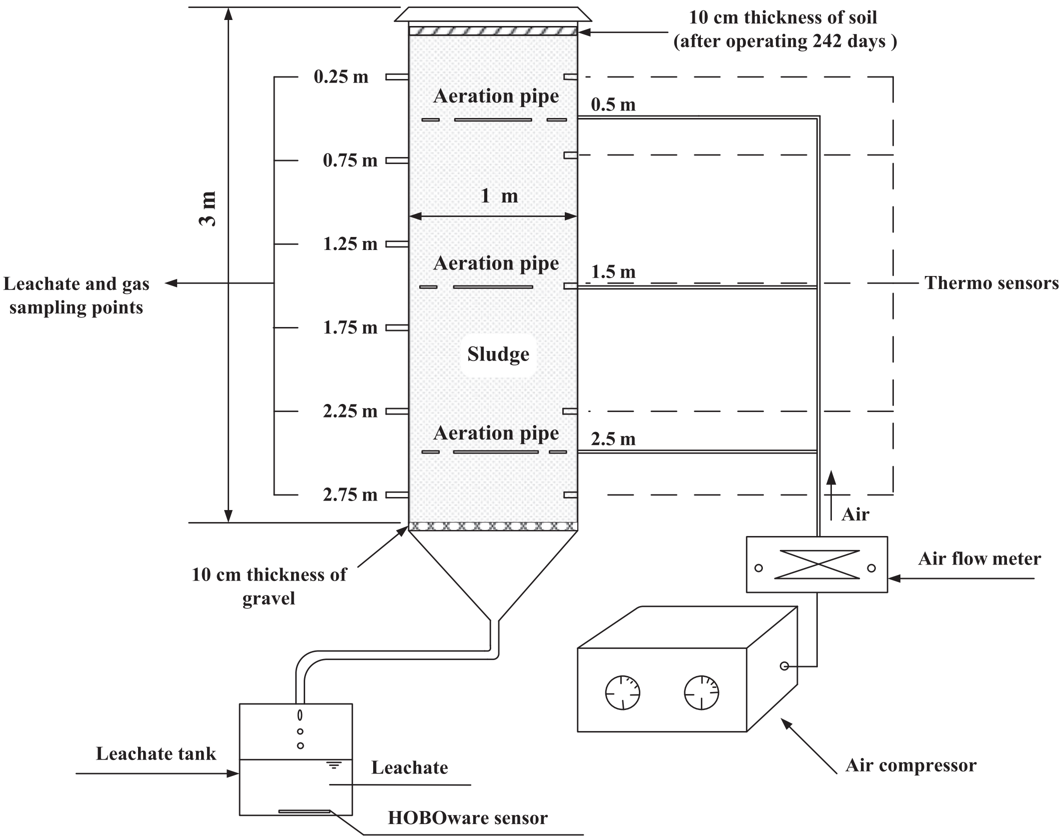

Figure 2. Schematic diagram of the simulator in the experiment.

Figure 3. Picture of the gas injection pipes.

Table 1. Cover soil characteristics.

Items	Thickness (cm)	Density (g cm^{-3})	Water content (%)	Ignition loss (%)
Average	10	1.29	17.15	6.47

(2002). The nitrite and nitrate levels were measured with an ion chromatography system (Dionex, ICS-1000) that was equipped with an AG11-HC column and a potassium hydroxide eluent.

A triple valve was fitted to a syringe and was connected to another triple valve, which was fitted on a gas collecting tube. Next, the syringe was used to extract LFG (landfill gas) from the simulators. After the samples were collected, the triple valve was closed, and the syringe was sealed. Oxygen and methane concentrations were analysed with a gas chromatograph (GC) (Agilent Micro GC 3000) that was equipped with a TCD detector and a molecular sieve column. The concentration of carbon dioxide was separated with a Plot U column. Each sample was measured at least twice, and the average value of these measurements was used.

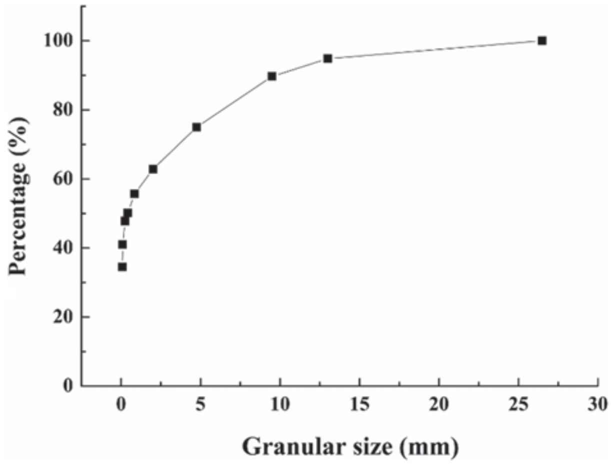

Figure 4. Granular size distributions of cover soil.

Table 2. The mass compositions of the refuge (%).

Average	Weight (g)	Content (%)
Waste paper	55.1	1.01
Cloth	54.2	2.30
Plastic	185.7	4.69
Rubber and leather	13.2	0.24
Wood bamboo and straw	387.5	6.59
Kitchen waste	345.8	5.93
Metal	40.6	1.07
Glass	264.8	6.61
Ceramics and stone	1539.4	28.70
5 mm particle size or less	2139	42.85
Sum total	5025.3	100

Table 3. Refuge characterization.

Items	Thickness (m)	Density (t m^{-3})	Water content (%)	Ignition loss (%)	Saturated hydraulic conductivity (cm s^{-1})	pH
Average	3	1.33(wet)	42.2	24.8	0.02	7.48

Results and discussion

Landfill gas characterization

Figure 5(a) illustrates the spatial distribution of oxygen in the three simulators. Significant differences were observed between the three simulators. Oxygen concentrations in simulator B were relatively higher and more even across all depths than in the other simulators. In addition, a high oxygen concentration was observed at all depths in the three simulators at 55 and 186 days. The high oxygen concentration was followed by reduced oxygen concentrations, which were attributed to temperature variations. On days 55 to 186, the temperature was significant lower than during the other operation times (Figure 6). These low temperatures potentially weakened the metabolism of the micro-organisms. Thus, the oxygen carried by the diffusing air was abundant. After day 186, the increasing temperatures accelerated the microbial activity, which resulted in the consumption of oxygen. Although no distinct differences in the spatial distribution of oxygen were observed between simulator A and C, the oxygen concentrations decreased with increasing depth. Although air was injected into simulator A, its upward diffusion was likely due to the high moisture content and the density of the deeper layer, which resulted from settling.

The concentration of carbon dioxide increased with depth in simulator A and C (Figure 5(b)), which was explained by the higher density of the deeper layers. This increased density inhibited carbon dioxide emissions and promoted their accumulation. In simulator B, the opposite trend was observed because the injected air occupied the bottom pore space, which diluted the carbon dioxide concentration.

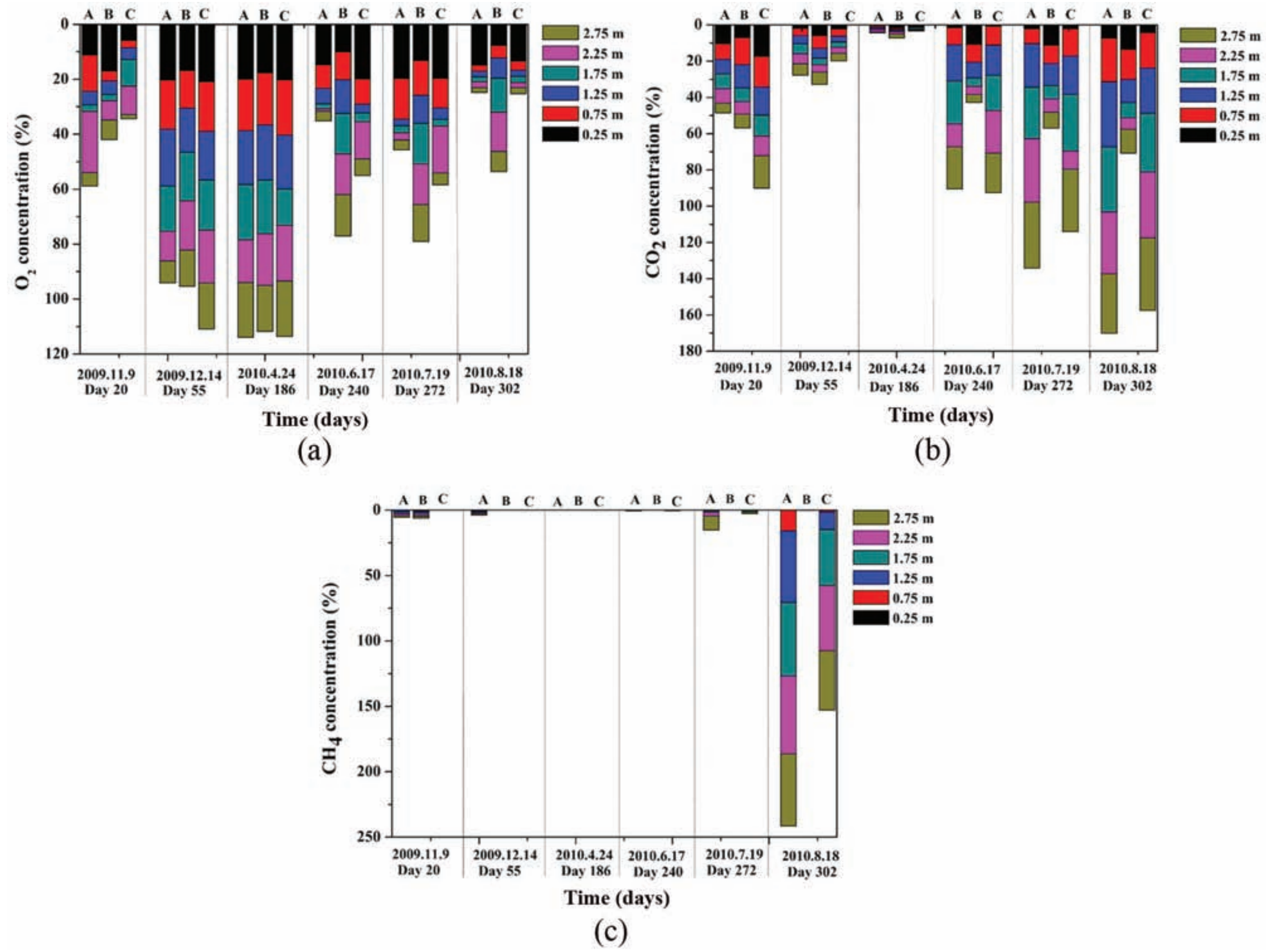

Figure 5. Spatial distribution of LFG character in three simulators: (a) O_2; (b) CO_2; (c) CH_4.

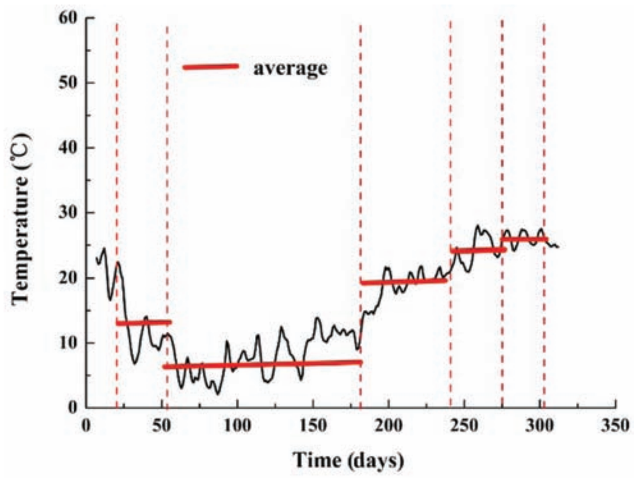

Figure 6. Temperature variation with time.

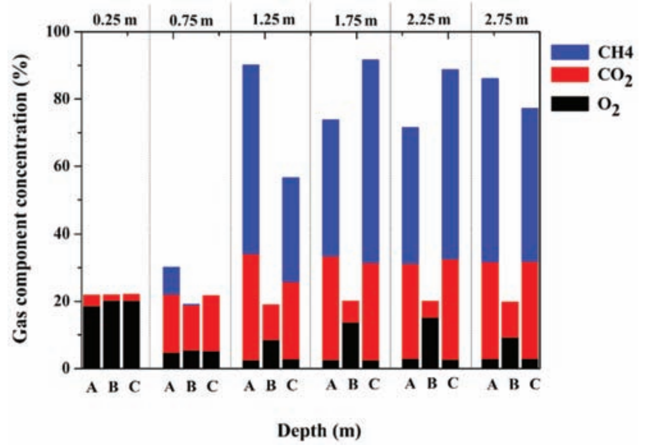

Figure 7. Spatial distribution of the LFG character in the three simulators on day 312.

A 10 cm thick layer of soil was placed over the surface of the refuge at 240 days, which inhibited the diffusion of air and promoted the formation of anaerobic zones. The effect of the cover soil was apparent when methane emissions were observed after 240 days (Figure 5(c)). In addition, the CH_4 concentrations increased faster than the CO_2 concentrations in the landfill. However, nearly no methane was detected in simulator B.

The spatial distributions of O_2, CO_2, and CH_4 in the three simulators on day 312 are shown in Figure 7. High oxygen concentrations were observed in all three simulators at a depth of 0.25 m, which suggested that the high oxygen concentrations in the upper layers resulted from air diffusion rather than from the injected air. In simulator B, oxygen concentrations at depths of 0.75 and 1.25 m were relatively lower than at the other depths.

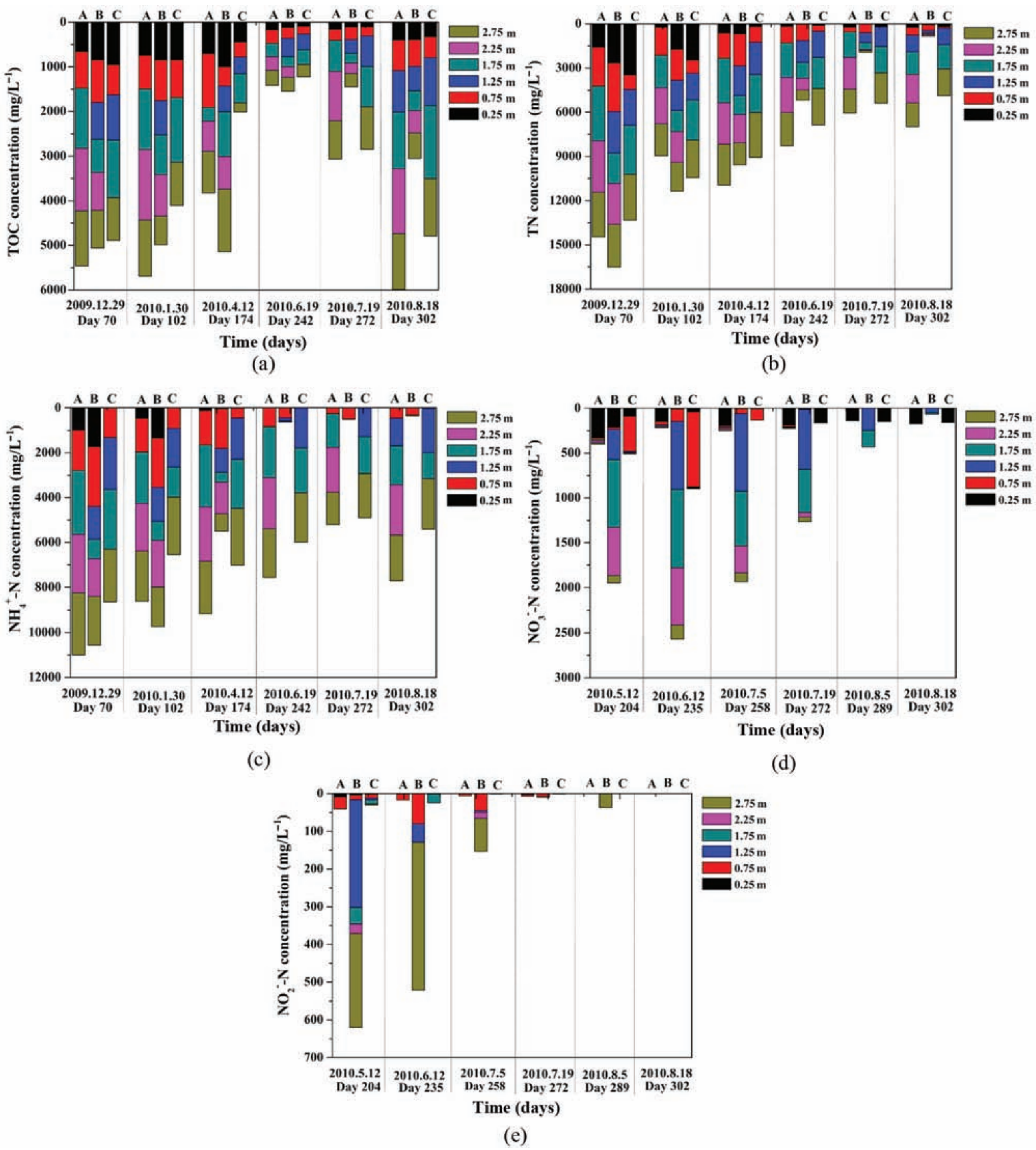

Figure 8. Spatial distribution of the leachate character in the three simulators: (a): TOC; (b) TN; (c) NH_4^+-N; (d) NO_3^--N; (e) NO_2^--N.

These lower oxygen concentrations resulted from the consumption of oxygen by micro-organisms. No methane was observed at any depth in simulator B. However, high methane concentrations were detected in the deeper layers of simulators A and C, which demonstrated that bottom aeration systems can significantly reduce methane levels. Thus, bottom aeration systems are a potential method for GHG emission management.

Because the bottom of the simulator is connected to the leachate tank directly through pipes, a small level of ambient air can seep in through the leachate tank and pipes. This seepage of air can account for the low oxygen concentrations at the bottom of the simulators. Peng (2004) pointed out that a hybrid mix of gas and liquid can be expected to be mobile in the landfill body, which further complicates the movement of gas. In addition, gas permeability increases when gas flow paths become wet. Thus, the gas samples just show the probably condition at that depth and the coexistence of oxygen and methane is more a result of this.

Leachate characterization

Spatial distribution of the leachate characteristics in the three simulators. As shown in Figure 8(a), the concentration of TOC in simulators A and C increased with depth and was distributed evenly at all depths in simulator B. The spatial distribution of TOC in the three simulators corresponded to the spatial distribution of O_2. The TOC concentrations were reduced before 242 days (particularly from days 174 through 242) and increased after 242 days. This reduction resulted from an increased conversion of carbon from a liquid to gas, which led to an increase in carbon gas discharge. This trend was supported by the higher carbon dioxide concentrations shown in Figure 5(b). The subsequent increase is likely because carbon more rapidly transforms from a solid to a liquid than from a liquid to a gas.

With respect to the spatial distribution of nitrogen, an analogous distribution of TN and NH_4^+-N was observed in simulators A and C. This distribution suggested that ammonia nitrogen was the dominant form of nitrogen in both anaerobic conditions (Figure 8(b) and 8(c)). In simulators A and C, the concentrations of ammonia nitrogen and TN increased within the layer of depth 0 to 1.25 m, and had a consistent concentration as the depth increased from 1.25 m. This is because the excess oxygen causes nitrification, the process in which ammonia nitrogen is oxidized to nitrate. The existence of anaerobic pockets (Berge et al., 2005) causes denitrification, which leads to reduced nitrogen concentrations in the upper layers. The occurrence of simultaneous nitrification and denitrification were further demonstrated by the relatively higher nitrate and nitrite concentrations in the upper layers (Figure 8(d) and (e)).

Ritzkowski and Stegmann (2003) observed that a large amount of nitrogen was discharged from ammonia stripping the gas phase. However, air stripping and volatilization may occur in aerobic bioreactor landfills as a result of higher pH values and temperatures (Berge et al., 2005). However, nitrogen was probably not removed by stripping and volatilization because the pH in simulator B was nearly neutral and the temperature was not high. Therefore, the reduction of nitrogen was mostly a result of denitrification.

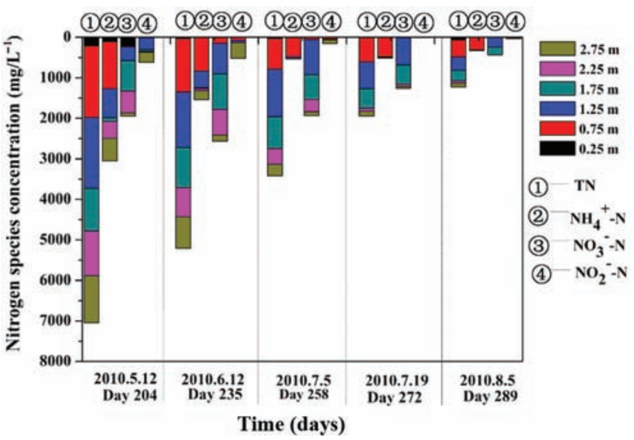

Figure 9. Spatial distribution of nitrogen in simulator B.

The spatial distribution of nitrogen in simulator B is illustrated in Figure 9. The concentration of TN increased at depths of 0 to 1.25 m. There was a reduction as the depth increased, followed by a steady and low concentration of TN. At a depth of 0.75 m, ammonia nitrogen was the dominant nitrogen species. At the depth of 1.25 m, all three species were present. The relatively lower oxygen concentration and the constant TN concentration at this depth suggested that the nitrification was incomplete. Thus, the presence of nitrite was attributed to the oxidization of ammonia nitrogen rather than the reduction of nitrate. The lower concentration of TN at depths of 1.25 to 1.75 m confirmed that denitrification had occurred. At depths of 1.75 to 2.25 m, the higher oxygen availability made it possible for the oxidation of ammonia nitrogen into nitrate. At a depth of 2.75 m, all three nitrogen species were present. All of the results indicated that a transition between nitrification and denitrification occurred in simulator B due to the distribution of oxygen, which led to nitrogen reduction.

The present investigation on the spatial distribution of nitrogen in aerobic conditions is important because it explores a new mechanism for nitrogen removal. Simultaneous nitrification and denitrification during aerobic conditions can lead to nitrogen removal. However, the interchange of nitrification and denitrification in the longitudinal direction also contribute to the reduction of nitrogen.

Variation of nitrogen in the leachate tank. Figure 10 shows the spatial distribution of the four nitrogen and TOC species in the leachate collected from the collecting tank. Simulator B had high organic carbon and nitrogen removal efficiencies, especially for the removal of ammonia nitrogen. At the end of the investigation, the ammonia nitrogen concentrations in simulators A and C were 514 and 530 mg L^{-1}, respectively, while no concentration of ammonia nitrogen was detected in simulator B. In addition, the TN concentrations in the A, B and C simulators were 659, 78, and 626 mg L^{-1}, respectively, which indicated that the bottom aeration system removed a significant amount of TN. In addition, the TOC concentration was significantly lower in simulator B than in simulators A and C. The final concentrations of TOC in simulators A, B and C were 828, 204 and 1012 mg L^{-1}, respectively. After a 10-cm layer of soil was placed on the surface of the refuge after 240 days, the concentration of nitrate and nitrite decreased considerably. This decrease occurred because the soil inhibited the diffusion of oxygen and favored the formation of anoxic zones.

The NH_4^+-N concentrations in simulators A and C were high because nitrification was restrained by TOC concentrations in both simulators. It is widely acknowledged that the bacteria responsible for nitrification are autotrophic, and their propagation is restrained by high concentrations of organic compounds. The pH of the leachate in all three simulators was around 8 and remained stable throughout the investigation. This was because the refuge had been in landfills for 5 years, which had passed the acidification stage. In this study, the similar concentration of TOC and nitrogen in simulators A and C suggested that the top aeration system was not effective for TOC and nitrogen removal. However, a study by He and Shen (2006) showed that intermittent aeration

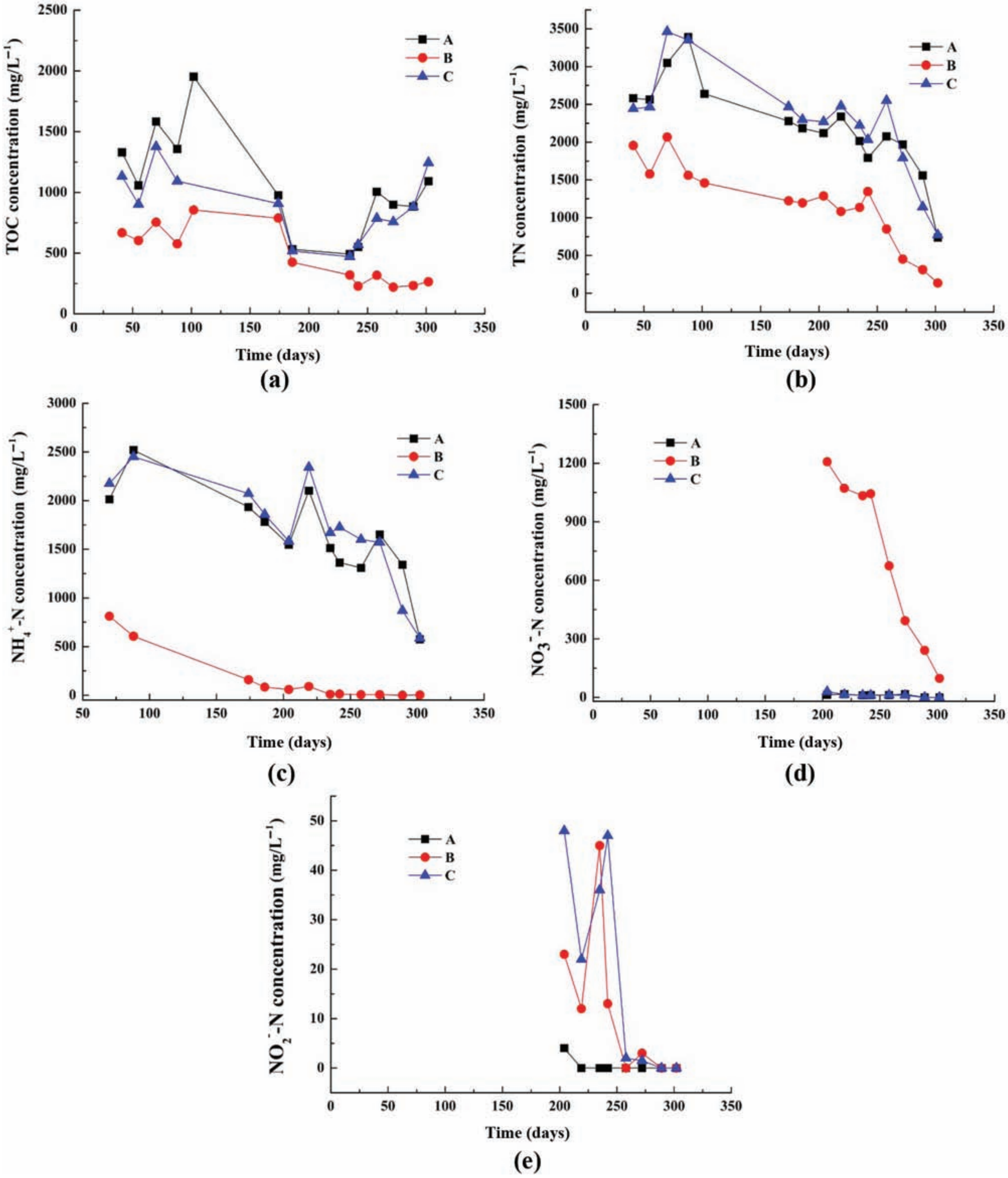

Figure 10. Variation of leachate quality in the three simulators: (a) TOC; (b) TN; (c) NH_4^+-N; (d) NO_3^--N; (e) NO_2^--N.

at the top of landfill waste helped to effectively remove ammonia and total nitrogen. However, this result occurred from an UASB ex situ leachate treatment (up-flow anaerobic sludge bed).

Conclusions

The investigation of the bottom aeration system was favorable for promoting oxygen distribution and inhibiting methane production. The spatial distribution and reduction of pollutants and especially that of nitrogen, corresponded well with the oxygen distribution. The transition between nitrification and denitrification in the longitudinal direction of simulator B contributed to high ammonia removal from the leachate. This process can be regarded as a new mechanism of nitrogen removal in aerobic conditions. In addition, a significant reduction of TOC and TN occurred in the leachate of simulator B relative to simulators A and C. All of the investigations suggested that the bottom aeration system was more efficient for inhibiting methane production, nitrogen removal and TOC reduction than either the top aeration system or no aeration system.

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