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Influence of Stand-Alone Vertical Gas Vents on Aeration and Denitrification of Organic Municipal Waste Assessed by Two-Dimensional (2D) Lysimeters

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Abstract

Landfilled organic waste, in the presence of oxygen, can undergo aerobic decomposition facilitated by heterotrophic microorganisms. Aerobic degradation of solid waste can quickly consume available oxygen thus curtailing further degradation. The aim of this study was the investigation of a low-cost method of replenishing oxygen consumed in landfilled waste. Three 2D lysimeters were established to investigate the effectiveness of stand-alone, vertical ventilation pipes inserted into waste masses. Two different configurations of ventilation were tested with the third lysimeter acting as an unventilated control. Lysimeters were left uninsulated and observed over the course of 6 months with regular collection of gas and leachate samples. Lysimeters were then simulated for Oxygen (O_2) and Nitrous oxide (N_2O) to analyze the denitrification contributions of each. The experiment revealed that a single ventilation pipe can increase the mean oxygen level of a 1.7 m × 1.0 m area by up to 13.5%. It also identified that while increasing the density of ventilation pipes led to increased O_2 levels, this increase was not significant at the 0.05 probability level. A single vent averaged 13.67% O_2 while inclusion of an additional vent in the same area only increased the average to 14.59%, a 6.7% increase. Simulation helped to verify that lower ventilation pipe placement density may be more efficient as in addition to the effect on oxygenation, denitrification efficiency may increase. Simulations of N_2O production estimated between 8% - 20% more N_2O being generated with lower venting density configurations.

Keywords

Organic Waste, Waste Stabilization, Passive Aeration, 2D Lysimeter, COMSOL

Multiphysics, *In-Situ* Aeration

1. Introduction

Landfilled municipal solid waste (MSW) undergoes transformations, which has been grouped into 5 distinct stages (Cossu et al., 2018; Letcher & Vallero, 2019). Phase I, hydrolysis or aerobic phase, begins from the initial waste placement into cells as it immediately undergoes aerobic decomposition utilizing residual oxygen contained within the pore spaces at the time of layering and covering. Next, transitory phases (II + III) begin as oxygen is gradually consumed by heterotrophic, aerobic microorganisms. Under anoxic conditions, the methane fermentation phase or anaerobic phase (phase IV), which is characterized by methanogens or methane forming bacteria dominance, begins. The final phase, V, termed the maturation phase, where the waste mass is stabilized, and methane production is significantly reduced.

The anaerobic phase of landfills is associated with the production of landfill gas (LFG), whose constitution is comprised of approximately 55% - 65% methane and 35% - 45% carbon dioxide (Christensen et al., 2020). Globally there has been an increased effort to minimize fugitive methane gas emissions due to their significant contribution to global warming. LFG, specifically methane, has value as an energy source but in cases where its collection is not feasible or viable, *in-situ* aeration tactics have been implemented to assist in minimizing methane emissions as a post closure remediation mechanism (Ritzkowski & Stegmann, 2013). This led to numerous studies (Ritzkowski & Stegmann, 2012, 2018) on active aeration concepts where air is forcibly introduced into landfills, consuming energy via injection (positive aeration) or suction (negative aeration). An alternative *in-situ* aeration concept which has not been as extensively researched is the use of passive air vents. Traditionally, passive vents have been installed at landfills as a means of venting LFG from the landfill to the atmosphere to reduce LFG accumulation within the landfill mass. These traditional shafts can be perforated along most of their length to allow LFG created at any depth entry. Modification of these vents to contain perforations solely at the lower end, concentrated delivery of air into the waste can be achieved. This movement is driven by negative pressures created as LFG escapes (Ritzkowski & Stegmann, 2012). On-site studies analyzing the effect of passive aeration vents as a remediation mechanism showed that vents can be effective in delivering air to the lower regions of a landfill body if there is organic matter present (Kim et al., 2010). Kim et al. (2010) deduced that the vents facilitated aerobic degradation of organic matter which induced temperature increase, which drove convection within the waste leading to LFG rising and exiting while air entered. This gas movement created by the presence of standalone vertical vents mirrors the effect created by the semi aerobic method of landfilling. In the semi aerobic method, natural ventilation of waste is promoted via enlarged leachate collection pipes connected to vertical aeration pipes. Gas generated is removed from the waste mass via convection, driven by the residual heat from decomposition which allows for ambient air to enter via the leachate collection pipes promoting rapid stabilization of waste (Matsuto et al., 2015). Globally it is estimated that approximately 37% of waste is treated using landfills with only 8% of these landfills containing gas collection systems (Kaza et al., 2018). Of the remaining waste up to 33% is disposed of in open dumps, predominantly in low income/developing countries. To minimize impact on the natural environment these existing anaerobic and uncontrolled landfills should require rehabilitation methods which can be implemented during the operating or post closure phases. With most of these sites located in low-income countries rehabilitation should be low cost and simple to implement.

Passive aeration vents can be considered as an alternative, low cost, in situ landfill rehabilitation method which can be suited to rehabilitation of landfills in low income/developing countries. The current study aims to help clarify the applicability of vertical ventilation pipe installation at landfill sites in developing countries as a means of landfill improvement and or rehabilitation. This was assessed by visualizing the effect on gas distribution within a waste mass that occurs in the presence of stand-alone vertical gas ventilation pipes utilizing 2D lysimeters. Other investigations such as (Kim et al., 2010) were undertaken at situ at existing sites in the latter phases of the landfill lifecycle with depleted organic content. The use of lysimeters allowed for organic content to be standardized and for the investigation of the effect of vertical vents being implemented in waste of elevated organic content. To the authors' knowledge, there have been no other investigations utilizing 2D lysimeters to investigate stand-alone passive aeration. Experimental data was utilized in the development of a simulation which was utilized to forecast and visualize the changes in parameters not directly measured.

2. Materials and Methods

2.1. 2D Lysimeter

Three steel lysimeters were constructed with dimensions shown in **Figure 1** & **Figure 2**. One face of each lysimeter contained sampling ports as pictured in **Figure 1** & **Figure 3**. The other face was composed of glass for observation of the filled contents as seen in **Figure 4** S-trap pipes were attached to each lysimeter to ensure leachate release while simultaneously preventing air entry from below.

2.2. Ventilation Shaft

Two types of steel ventilation shafts were utilized: long and short. Long shafts were 1150 mm in length and spanned from the drainage layer at its lowest point and extending to 50 mm above the upper surface of the lysimeter at its highest point. The short shaft was 750 mm in length. Apart from length, all shafts were of equal thickness and width. The final 200 mm of each shaft were perforated with 10 mm diameter openings as can be seen in **Figure 5**. The perforations were covered with a mesh to minimize clogging on insertion into the lysimeter.

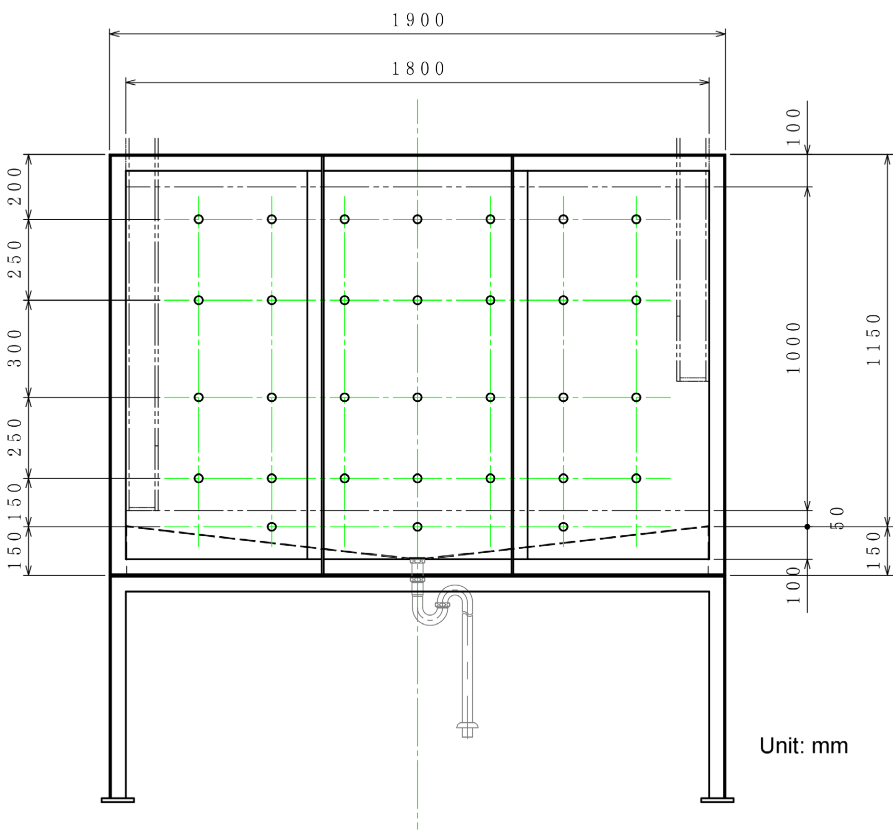


Figure 1. 2D Lysimeter rear view.

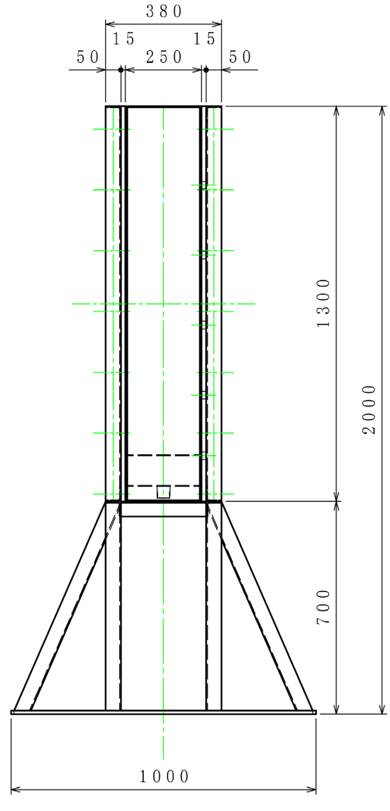


Figure 2. 2D Lysimeter side view.

Figure 3. Lysimeter Rear view showing gas sampling ports.

Figure 4. Filled Lysimeter front view-2 vents.

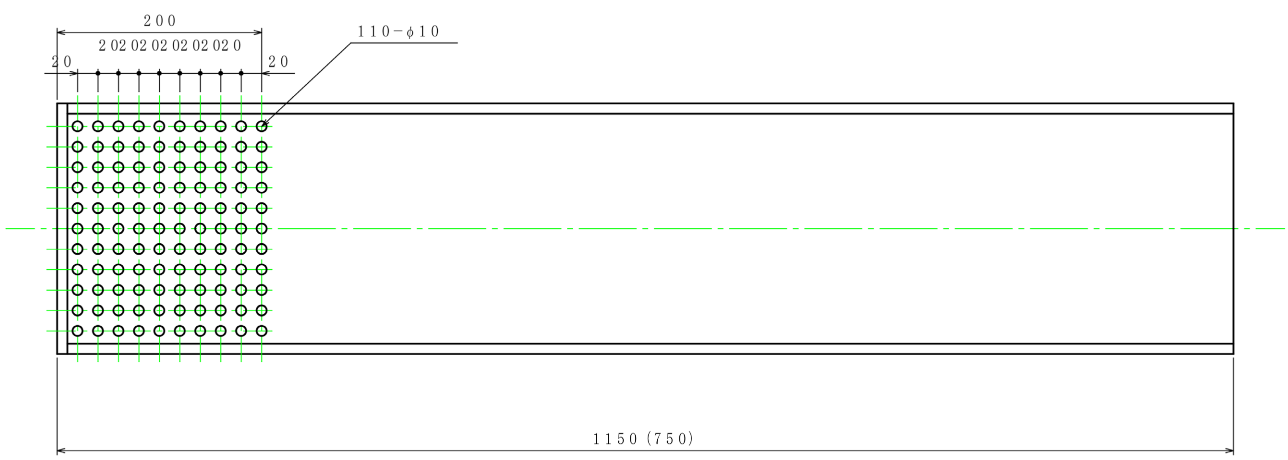


Figure 5. Ventilation shaft.

2.3. Layering

Each lysimeter comprised three layers: a. Topsoil, b. Waste Layer, c. Drainage layer.

1) Topsoil: 50 mm in depth and constituted of inert sand-gravel mixture.

2) Waste layer: 1000 mm in depth and composed of a mixture of 10% compost (CP) and 90% bottom ash (BA), on a dry weight basis. Compost was utilized to emulate the organic waste fraction while bottom ash was utilized as the inorganic fraction. Compost utilized was created from kitchen/food waste and was obtained from a retail gardening outlet. Bottom ash was obtained from a municipal waste incineration plant in Fukuoka, Japan. The waste layer was prepared by manually mixing the compost and bottom ash in the pre-determined ratio before adding it to the column in five layers. The layers were demarcated by the levels of gas ports to allow for the gas sampling apparatus to be safely inserted at each lift. Each layer was uniformly compacted to attain a dry density of approximately 1200 kg/m^3.

3) Drainage layer: The drainage layer consisted of course stone of less than or equal to 50 mm to facilitate leachate drainage and removal.

2.4. Layout

The first lysimeter, (A) was established as a control with no ventilation shafts. The 2nd lysimeter (B) contained only a long shaft while the final lysimeter (C) contained both a long and short shaft placed on opposite sides of the lysimeter. Long shafts in lysimeters B + C were placed on the same side. No thermal insulation was implemented during the experimental 6-month period which extended from summer to the beginning of winter.

2.5. Gas Sampling

Thirty-one gas samples were obtained from the sampling ports connected to each lysimeter initially at weekly intervals for the first 8 weeks. Samples were then withdrawn at approximately fortnightly intervals. Samples were extracted utilizing a 5 ml syringe and double 3-way stop valves; one valve was fixed to the sampling port of each lysimeter with the other attached to the sampling syringe. A maximum of 3 ml of air was extracted for each sample. Gas samples were analyzed for O_2, CO_2, CH_4 and N_2 via SHIMADZU GC-2014 gas chromatograph.

2.6. Leachate Sampling

Leachate samples were collected on a fortnightly after the first month of the lysimeters being established. Samples were analyzed for the concentrations of cations (Ca^{2+}, Na^+, K^+, Mg^{2+}), anions (Cl–, NO_3^-, SO_4^{2-}), Organics (TC, TOC, TN,), Nitrogen (TN, NH_4^+), pH, Oxidation Reduction Potential (ORP) and Conductivity (EC). Anions were analyzed by Dionex ICS 2100, Cations by Dionex ICS 1100 and TOC, TN using a Shimadzu TOC-V CPH Analyzer. pH and EC were analyzed using Horiba Laqua F47BW while ORP was tested using the

Horiba Navi F-51.

3. Results and Discussion

3.1. Initial Organic Concentration

The organic content of the waste layer materials was determined prior to mixing and placement in lysimeters. The loss on ignition (LOI) method, which is one of the most frequently utilized means of determining organic content in soils, was utilized. Samples were oven dried at 200˚C for 24hrs. The difference between the weight before drying and that after drying was interpreted as the weight loss due to moisture.

LOI was determined by ignition of the oven dried samples in a muffle furnace for 2 hours at 600˚C. The difference between the weight before and after ignition was interpreted as weight loss due to organic matter. Organic matter was converted to organic carbon utilizing a conversion factor of 0.55 $kg \cdot kg^{-1}$ (Hoogsteen et al., 2015).

Table 1 presents the result of LOI determination. CP utilized in the experiment contained, on average, 44% organic carbon, with BA containing insignificant quantities. Utilizing this data together with the lysimeter filling ratio of

Table 1. Waste layer organic content.

COMPOST			
Sample #	**Moisture Content (%)**	**Mass loss on ignition (%)**	**Estimated Organic Carbon (%)**
1	13.5	78.9	43.39
2	14.3	80	44.00
3	14	79.1	43.49
4	1	79.8	43.89
5	13.2	82.6	45.43
6	12.9	80.7	44.38
Mean	11.48	80.18	44.09
BOTTOM ASH			
Sample #	**Moisture Content (%)**	**Mass loss on ignition (%)**	**Estimated Organic Carbon (%)**
1	25.7	0.0	0.00
2	26.4	1.3	0.71
3	26.9	0.0	0.00
4	25.2	1.3	0.71
5	23.3	0.0	0.00
6	23.8	1.3	0.71
Mean	25.21	0.65	0.355

10% CP: 90% BA and the filling density of 1200 kg/m^3 the available carbon was estimated at 56 kg/m^3; approximately 5% of the mass of each lysimeter.

3.2. Initial Leaching

To establish the initial lysimeter compositions, samples were taken of the material used for each lift filled in the lysimeter. These samples were then subjected to leaching test JLT-46 established by the Japanese Ministry of the Environment. Table 2 presents the data obtained from the leaching tests. Data shows that while Lysimeter A showed some variation lysimeters B + C were relatively uniform.

3.3. Gas Distribution

The utilization of 2D lysimeters allowed for the determination of both the vertical and lateral oxygen distribution profiles. These gas profiles were visually rendered as gas contour graphs where zones which were not directly measured were interpolated. Figures 6-8 present the oxygen contour maps for each lysimeter in four-week intervals where the right of the figure represents the location of long vertical vents (Figure 7 & Figure 8) and the left being the location of the short vent (Figure 8).

The initial high concentration of oxygen in all lysimeters was attributed to air trapped in pore spaces during filling. This air allowed heterotrophic aerobic microorganisms to proliferate in all lysimeters utilizing available energy sources. As these organisms proliferated their consumption of oxygen exceeded the replenishment of air by diffusion. This oxygen demand created diffusion gradients between the simulated waste mass and the atmosphere. With the design of the experiment, oxygen was expected to diffuse from the surface of the lysimeter through the topsoil and waste layer and, in the case where shafts were installed, directly via the shafts to the targeted depth. In all lysimeters the oxygen concentration measured trended downwards over time from the start of the experiment. The change over time, as shown by the contour maps, was not continuous but tended to fluctuate. This was attributed to some possible leakage in the

Table 2. Filled waste lifts comparison.

LIFT	A. No vent				B. Single vent				C. Double vents			
	pH	ORP (mv)	TOC (mg/L)	TN (mg/L)	pH	ORP (mv)	TOC (mg/L)	TN (mg/L)	pH	ORP (mv)	TOC (mg/L)	TN (mg/L)
I	12.29	18	463.6	50.47	12.42	−79	670.9	95.18	12.48	−72	681.8	94.58
II	12.47	−33	652.3	85.06	12.48	−68	691.9	87.8	12.33	−71	682.9	98.98
III	12.42	−61	489.9	77.88	12.41	−72	456.6	64.98	12.49	−69	455.4	58.71
IV	12.36	−71	663.5	81.38	12.33	−77	593.7	80.64	12.43	−69	857.7	114.2
V	12.33	−72	449.8	59.29	12.29	−78	587.1	113	12.46	−68	563.9	81.53
Mean	12.37	−44	543.82	70.81	12.38	−75	600.04	88.32	12.44	−70	648.34	89.6

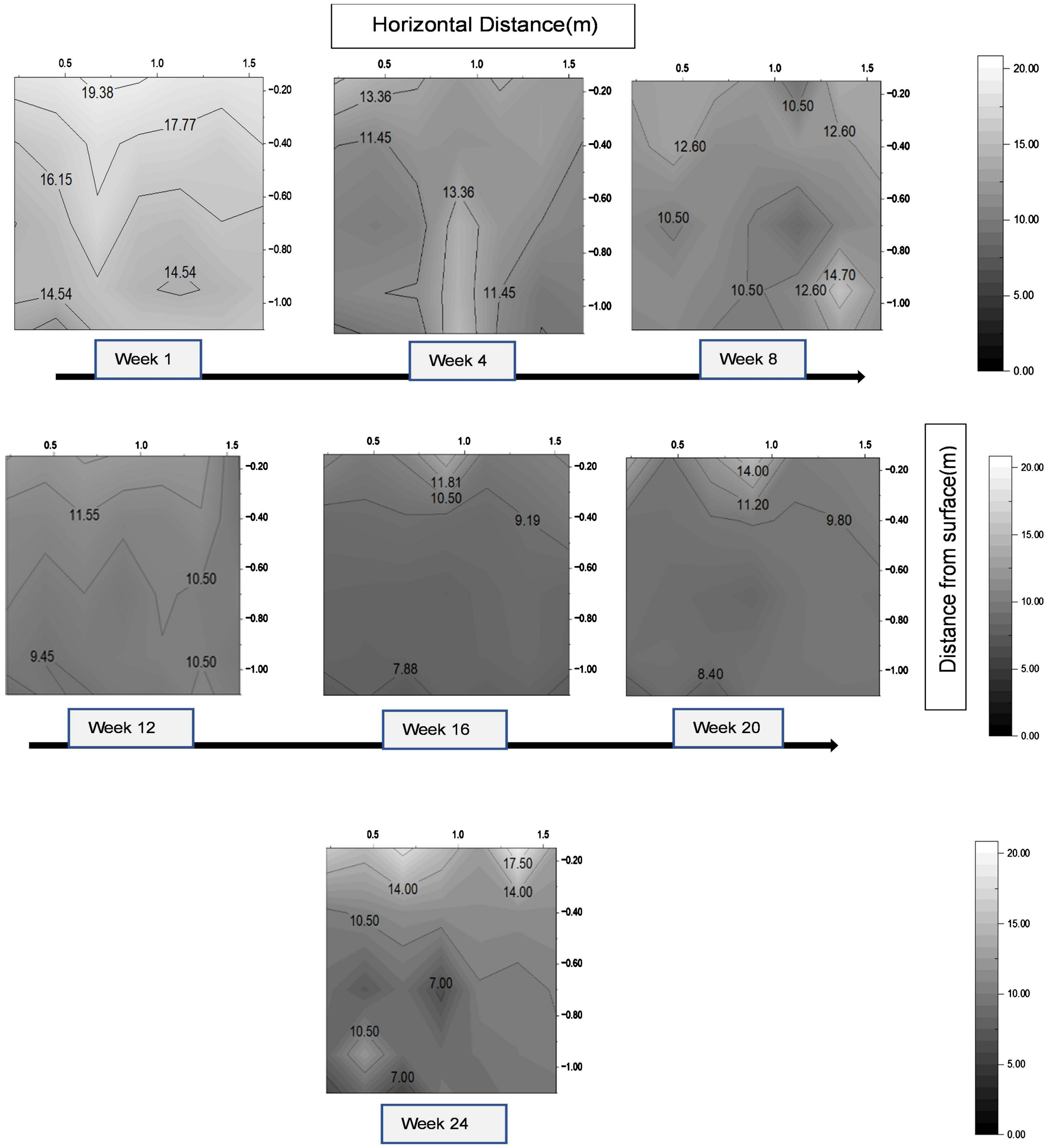


Figure 6. No Vents - O_2 (%) distribution.

lysimeters in addition to microbial hotspots, which are explored in a subsequent section. Despite this, the overall trend of oxygen levels being gradually depleted in organic waste was discernible.

The reduction in oxygen concentration over time was greatest in the lysimeter A with a minimum level as low as 7% measured while minimums of approximately 9.5% & 10.5% measured in B and C respectively. This demonstrated that

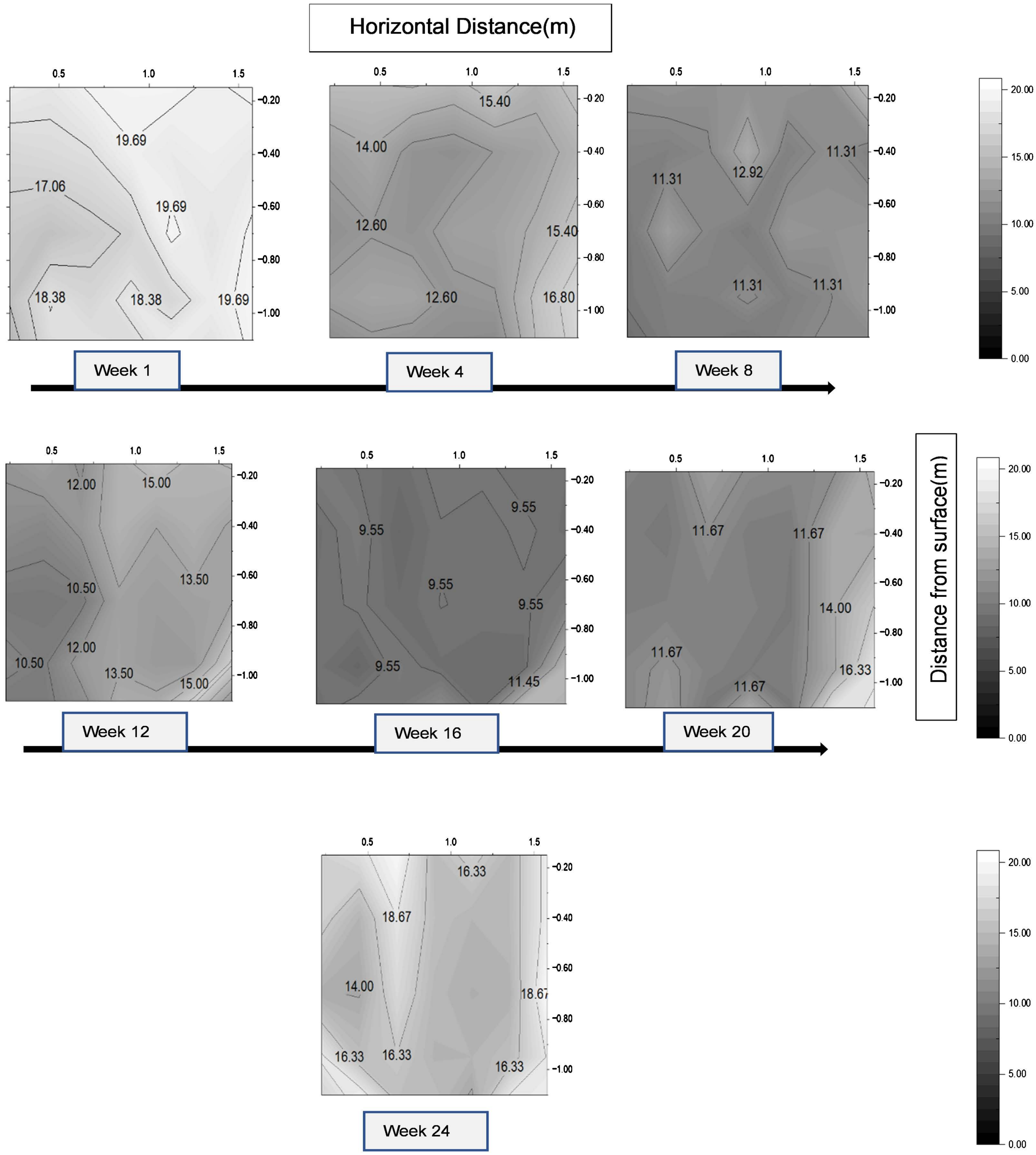


Figure 7. Single Long Vent (Right) - O_2 (%) distribution.

the presence of the shafts induces increased oxygen levels passively. Additional effects of the shafts were observed by looking at the lysimeter B where, in Figure 7, depths below 0.8 m there were consistently higher oxygen concentrations, ranging from 1% - 5%, where the long shaft was positioned (right side). This effect was also observed in the lysimeter C.

To quantify the effect of the passive vents the mean oxygen concentration of

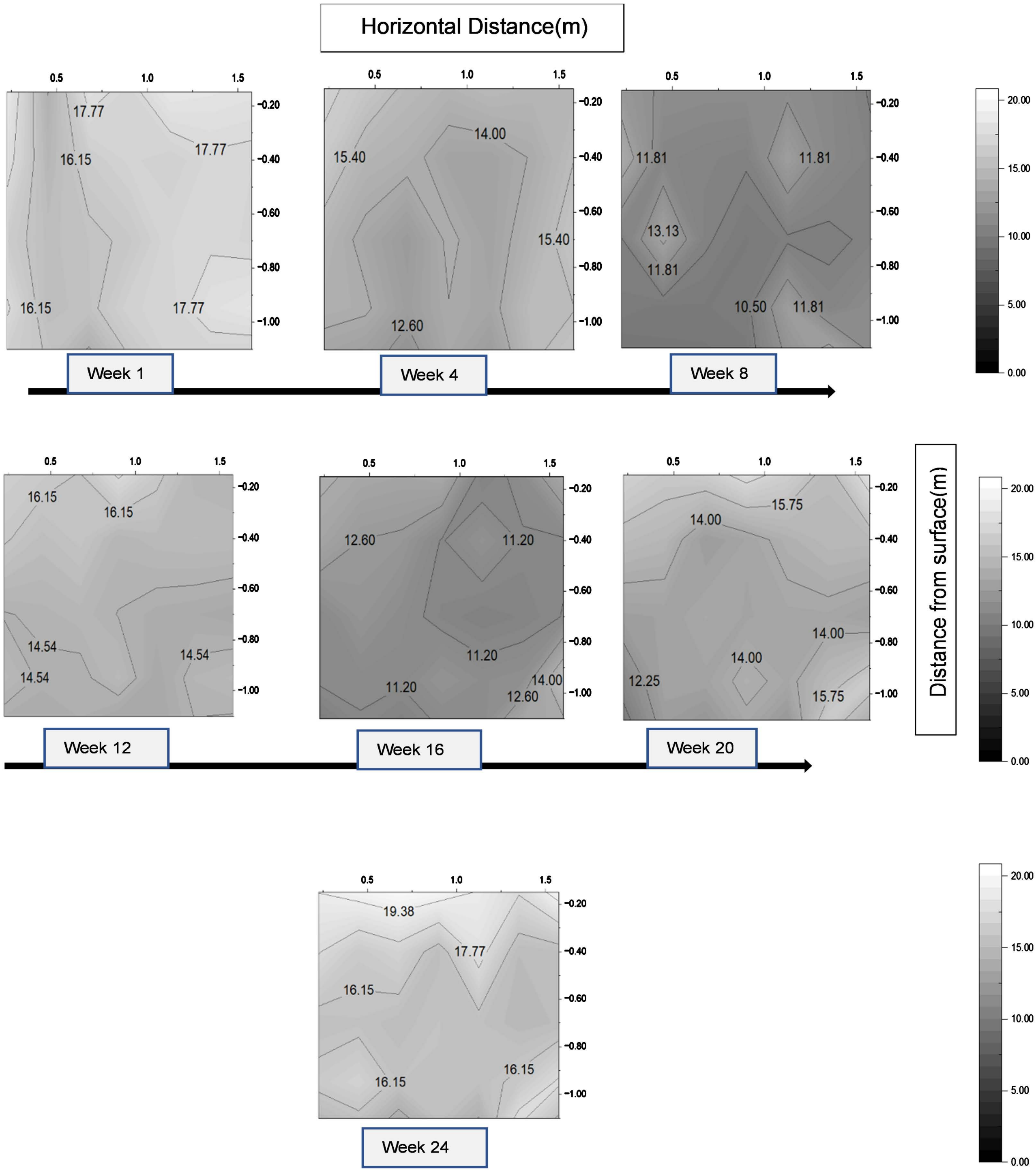
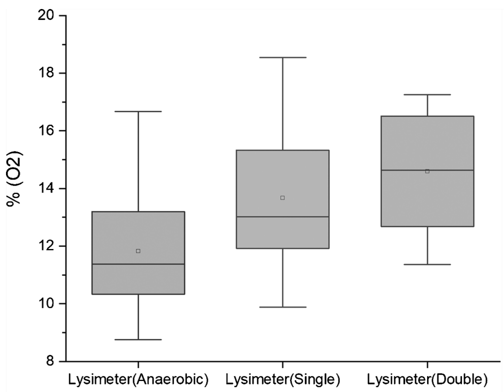


Figure 8. Short Vent (Left) Long Vent (Right) - O_2 (%) distribution.

each lysimeter for each sampling day was collated and subjected to a means test with the hypothesis that there was no difference between means. The summarized result for this analysis is presented in **Figure 9**. Using a significance level of 0.05 the analysis showed that, with a probability level of 0.000627 there is a significant difference in the mean oxygen levels between the lysimeter without vents (A) and the two with vents (B + C). Pairwise comparisons confirmed that lysimeters containing vents have a higher average O_2 concentration than that without, but the additional short vent did not produce a significant improvement compared to having only a single long vent. Lysimeter B averaged 13.67% O_2 while the additional short vent in lysimeter C only increased the average to 14.59%, a 6.7% increase. Comparison of Lysimeter's A and B showed a 15.7% increase in lysimeter B over A.

3.4. Leachate Quality

Leachate quality is closely correlated to the age and phase of decomposition of the waste mass (Kjeldsen et al., 2002). Typical leachate TOC concentrations ranging between 30 - 29,000 mg/L were reported by Kjeldsen et al. (2002). As can be observed in **Figure 10** the experimental lysimeters had initial concentrations ranging from 14 - 19,000 mg/L, near the higher end of the range reported



	Mean	Standard Deviation	Standard Error of Mean	Probability	Tukey Assessment *
Lysimeter(A)	***11.82***	***2.17***	***0.48***		***Y***
Lysimeter(B)	***13.67***	***2.32***	***0.51***		***Z***
Lysimeter(C)	***14.59***	***1.99***	***0.44***		***Z***
				6.27E-4	

Figure 9. Mean O_2 concentration.

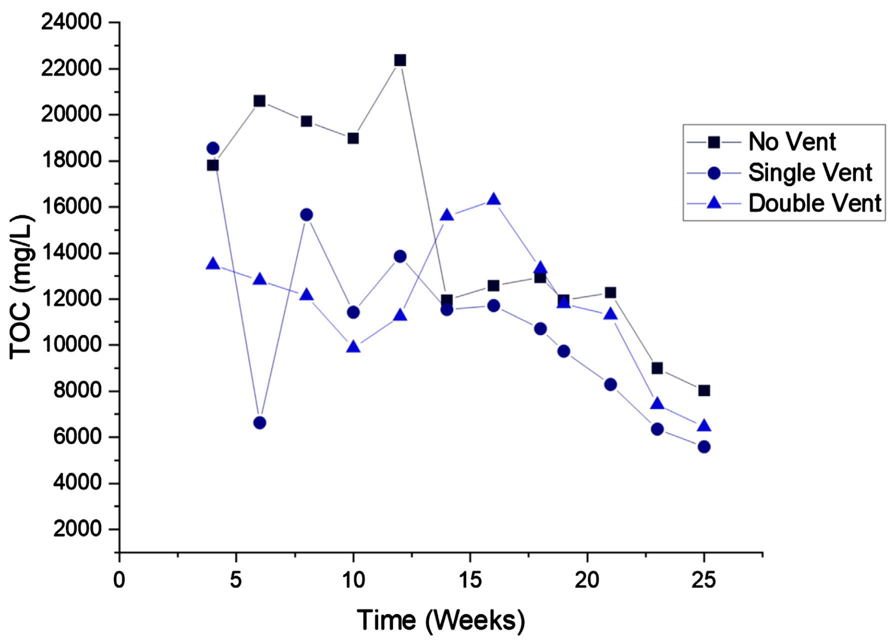


Figure 10. Leachate Total Organic Carbon (TOC).

by Kjeldsen et al. thus the organic load was comparable to landfills. Over the experimental period both ventilated lysimeters displayed lower TOC concentrations than the un-ventilated lysimeter. However, lysimeter B consistently displayed lower TOC levels compared to lysimeter C. Aeration experiments (Hrad & Huber-Humer, 2017; Slezak et al., 2015) typically show that higher oxygen levels created by aeration typically result in greater TOC reductions in leachate. It was therefore expected that lysimeter C with its higher absolute mean oxygen level would result in marginally better absolute TOC reduction. This did not prove to be the case with the lysimeter B seemingly demonstrating better absolute TOC reduction. It is surmised that this difference may be attributed to lysimeter B offering better conditions for the proliferation of myriad of heterotrophic bacterial species. The case for the lysimeter B promoting higher microbial growth is further increased when nitrogen is considered as in **Figure 11** & **Figure 12**.

Leachate ammonia nitrogen (NH_4-N) is a product of the decomposition of proteins, a process commonly termed ammonification (Kjeldsen et al., 2002). High concentrations are typically associated with mature leachate with an average concentration of 740 mg/L (Miao et al., 2019). Initially the lysimeter C generated greater NH_4-N but it was surpassed in weeks 8 - 16 by the single vent lysimeter suggesting that ammonification processes were accelerated by microbial proliferation.

The differences between the Lysimeter B and C could possibly be attributed to coverage provided by the vents. The presence of the second vent in the same volume created an even distribution of oxygen as visualized in **Figure 8** and quantified by the lower standard deviation in oxygen levels seen in **Figure 9**. The

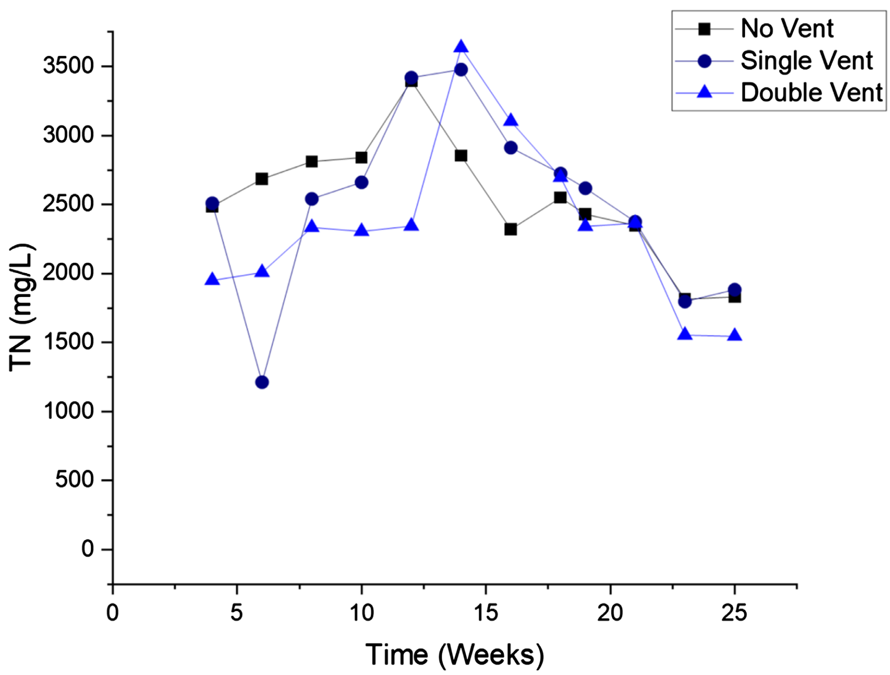


Figure 11. Leachate Total Nitrogen (TN).

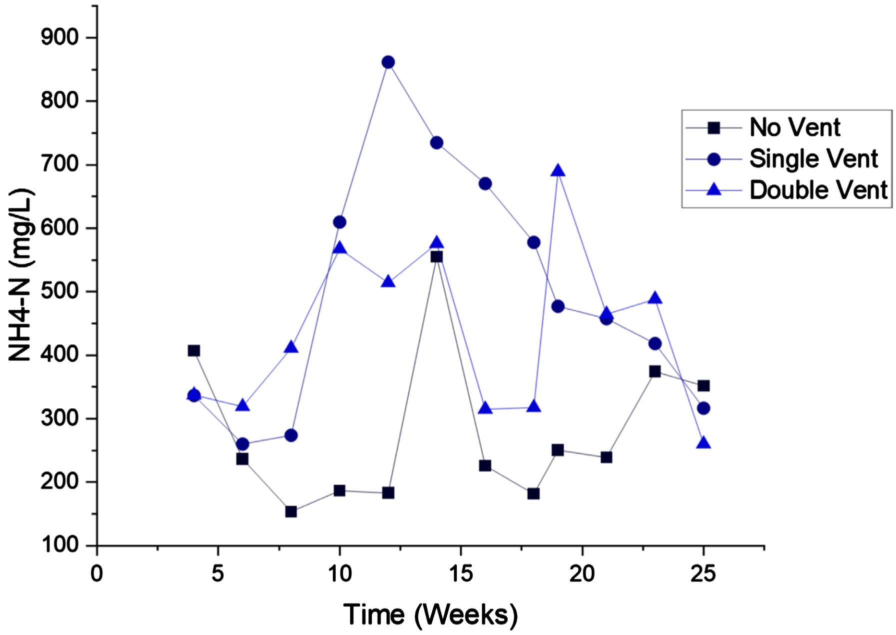


Figure 12. Leachate Ammonia Nitrogen (NH_4-N).

single vent lysimeter, on the other hand, had an uneven oxygen distribution with the unventilated side generally having a lower oxygen concentration. Therefore, an oxygen gradient developed between the ventilated and unventilated areas. The presence of this gradient could then allow for different species of microorganisms whose metabolism is optimized for specific oxygen ranges to develop microbial hotspots. Microbial hotspots can be defined simply as areas where favorable conditions lead to accelerated proliferation of microbes in a specific area compared to the surrounding areas. They have been identified in soil science (Kuzyakov & Blagodatskaya, 2015) and have been specifically researched and verified for their effect on nitrogen cycling (Bonkowski et al., 2000; Groffman et al., 2009; Schlüter et al., 2019).

NH_4-N is removed from leachate through nitrification processes which occur in the presence of oxygen as it is converted in successive steps into nitrites then to nitrates. (Ritzkowski et al., 2006) suggested that, under aerated conditions, simultaneous nitrification and denitrification processes lead to significant ammonia nitrogen reduction. Studies on intermittent aeration (IA) show that aerobic and anaerobic conditions do not need to be spatially separated but can be created temporally in the same waste area by alternating the aeration regime (Nag et al., 2016, 2018). In studies by Nag et al. (2016), it was observed that with aeration regimes of 3 days aeration and 4 days without aeration the greatest change in oxygen concentration observed was 20% immediately after aeration to 10% after the 4th day without aeration. Where aerated and anoxic zones occur in the same soil, nitrification-coupled denitrification can take place (Wrage et al., 2001; Zhu et al., 2015) in oxygen atmospheres between 5% - 15% (Hwang & Hanaki, 2000).

In the present study, the lysimeter A was typically in the lower oxygen range seen by Nag et al. (2016), the lysimeter C in the higher ranges while lysimeter B spanned most of the range based on the box plot in **Figure 9**. Given the oxygen gradient of the single vent lysimeter it could be concluded that the likelihood of nitrification-coupled denitrification and denitrification hotspots forming was increased. Increased nitrification could then contribute of the lower pH levels for the single vent lysimeter as seen **Figure 13** as nitrites and nitrates are acidic. While nitrifying bacteria are autotrophic, denitrifying bacteria are heterotrophic utilizing carbon substrates thus increasing TOC reduction.

3.5. Micro Bacterial Biomass

At the end of the experimental period, 3 leachate samples were taken at 2-3-week intervals for bacterial counts utilizing a standard agar method. As seen in **Figure 14** the single vent lysimeter consistently produced the highest aerobic bacterial counts. Reactor studies (Sang et al., 2009) demonstrated that diverse and unique bacterial communities are formed when intermittent aeration (IA) is undertaken. Taken together these factors suggest the single vent lysimeter presented the most optimal conditions for bacterial proliferation based on the measured data.

3.6. Simulation

In order to justify the perceived improvement presented by the single vent lysimeter analysis of denitrification processes were deemed necessary. A proxy to determine the occurrence of denitrification is to look at N_2O concentration. N_2O is formed as an intermediate in the denitrification process. Lysimeter N_2O concentrations were not within the original experimental scope so in order to investigate denitrification simulation was deemed the best option available. COMSOL

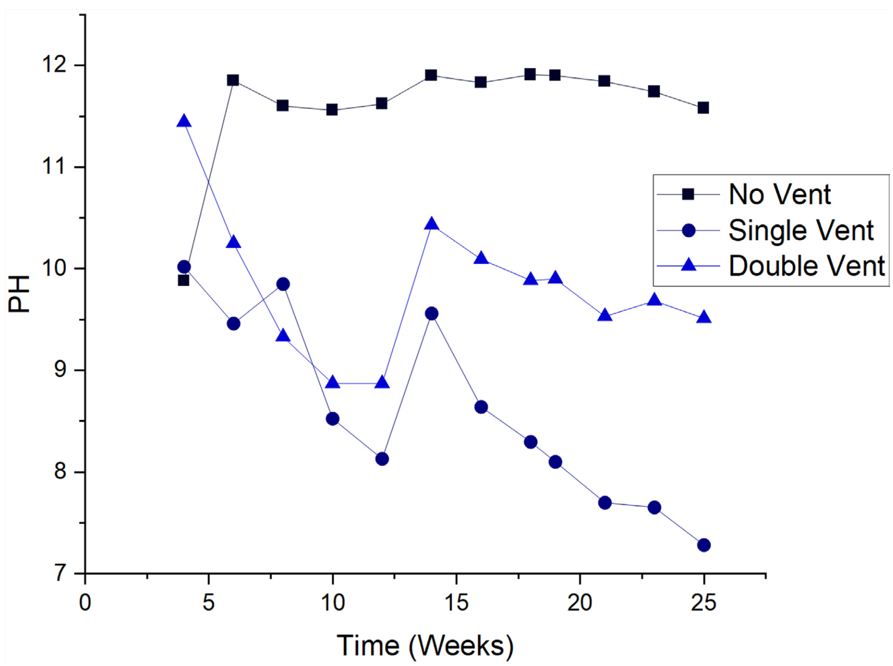


Figure 13. Leachate PH.

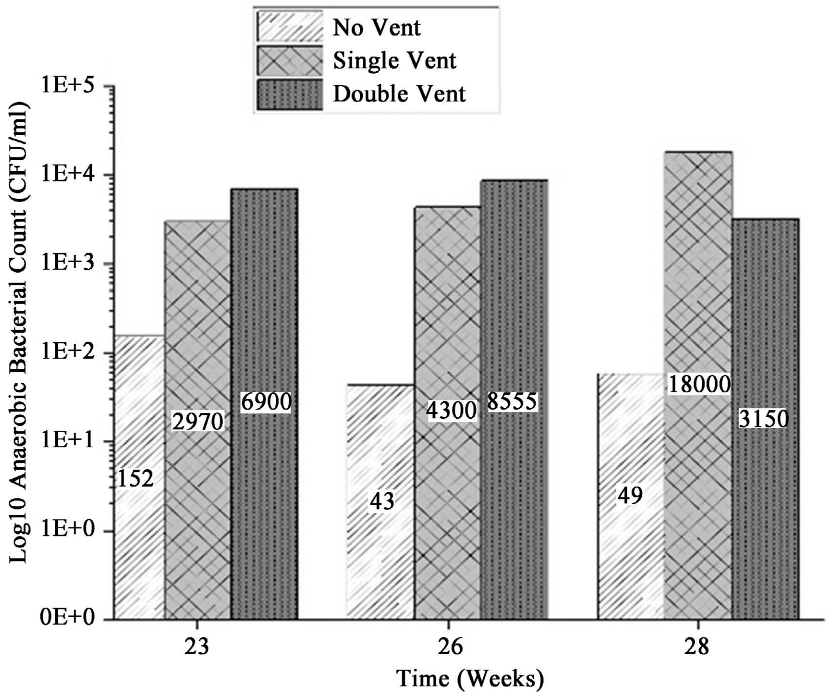


Figure 14. Aerobic bacteria count.

Multiphysics ™ version 5.4 was employed for the simulation with standard modules for heat transfer, diffusive gas transport and reactive chemistry implemented.

For simplification of the model the following assumptions were utilized.

1) Heat: lysimeter perimeter = No Flux; top of lysimeter and vents = open boundary.

2) Pressure: lysimeter perimeter = No Flux; top of lysimeter and vents = open boundary.

3) O_2 mass fraction = 0.21 at all zones at t = 0.

4) N_2O mass fraction = 0 at all zones at t = 0.

5) Temperature = 273 K at t = 0.

6) Pressure = 1 atm at t = 0.

Other parameters and kinetic models utilized in the simulation are presented in the appendix to this article.

Due to the importance of oxygen in both the promotion of nitrification and the inhibition of denitrification it was assumed that recreating similar oxygen profiles as seen in the lysimeter experiment would enable related processes to be modelled affectively. Figure 15 and Figure 16 show the comparison of the mean oxygen levels measured against the mean oxygen levels calculated via the simulation for each lysimeter respectively. Like the experimental data the simulated quantity was averaged only across the waste layer. Simulated values captured the overall trend with mean O_2 increasing with the number of vents showing a fit with experimental data. Nitrification kinetic models presented by (Chen et al., 2019) were then implemented to determine estimated N_2O generation. As

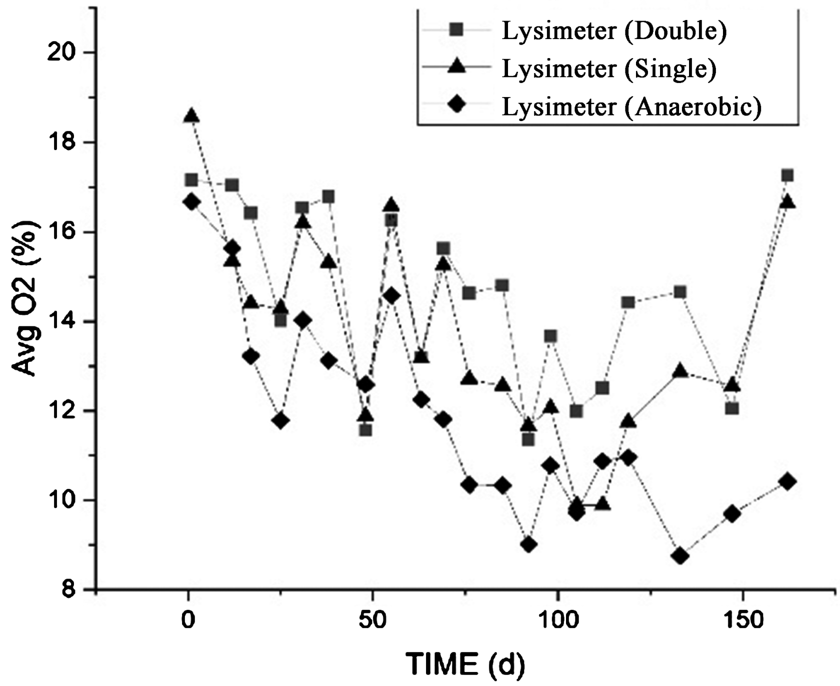


Figure 15. Mean O_2 concentration measured from experiment.

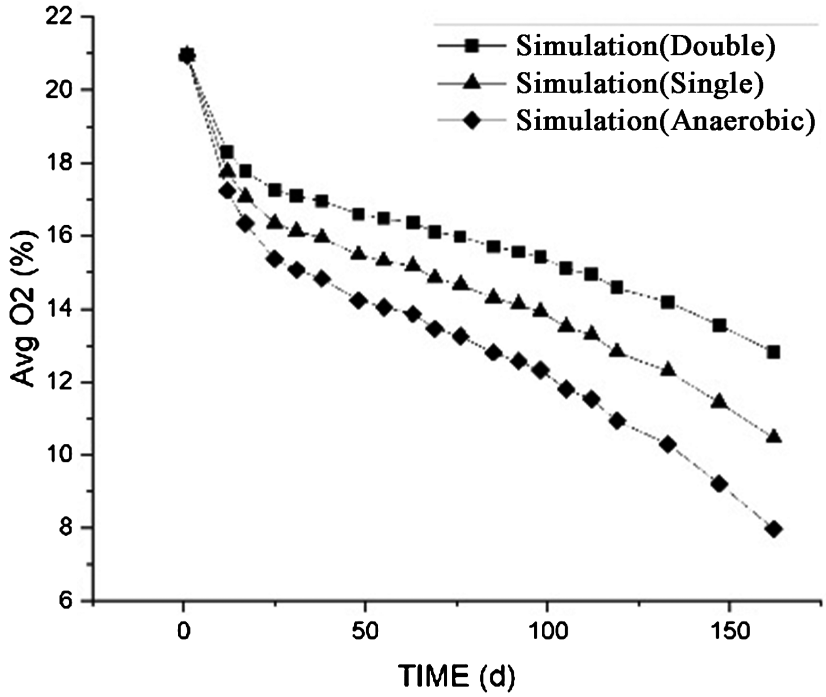


Figure 16. Mean O_2 simulated.

demonstrated in **Figure 17**, lysimeter A could be expected to generate N_2O at a slightly higher rate compared to the lysimeter B with the difference in generation simulated to range between 1% - 9%. The simulated rate of N_2O generation of lysimeter B exceeded lysimeter C by 8% - 27%. Based on this the single vented lysimeter provided anoxic conditions comparable to the unventilated lysimeter.

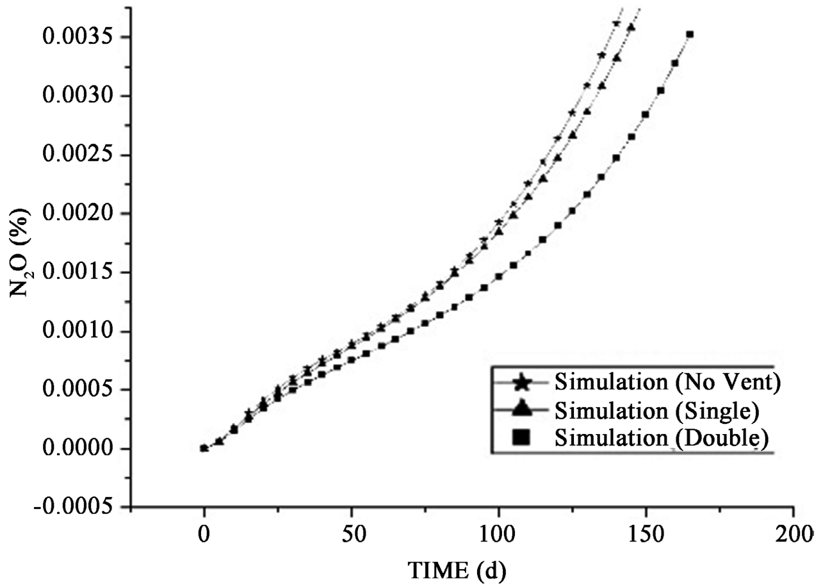


Figure 17. Mean N_2O - Simulated.

4. Conclusion

The inclusion of purpose-built ventilation shafts into waste bodies was effective in delivering oxygen into the lower regions of a waste mass without the need of forced aeration mechanisms.

Increased oxygen in waste generated faster TOC reduction but, as other works on intermittent aeration have shown, could have also inhibited other beneficial bacterial processes which require anoxic conditions to proliferate. The creation of both aerobic and anaerobic conditions separated spatially appeared to be an optimal solution. The insertion of passive aeration vents could serve as an alternative to intermittent aeration by removing the need for energy expenditure while still creating similar conditions. The choice in frequency/arrangement of passive vents may affect the balance between adequately aerated and anoxic zones and must be taken into close consideration.

Further work is needed to analyze the extent of denitrification which these passive aeration systems can facilitate compared to traditional intermittent aeration methods.

Supplementary Data

https://docs.google.com/document/d/1wzWABI2ihD6OvIMi-0uQqhL4-HSCCes9/edit?usp=drive_link&ouid=115705340196581833566&rtpof=true&sd=true

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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