

HETEROGENEITY OF OXYGEN CONSUMPTION IN ORGANIC SOLID WASTES

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Abstract— *In many developing countries a vast majority of the solid waste is disposed, untreated, to landfill sites. As much as 70% of these wastes are considered as some form of easily degradable organic matter. The presence of available organic matter creates a constant demand for oxygen from aerobic, heterotrophic microorganisms which affects the diffusion and distribution of oxygen in waste. While oxygen intrusion into soils is usually studied in the context of its utilization by plants in agriculture or other similar applications, this study attempted to visualize the distribution and consumption of soil oxygen in landfill environments where respiration by microfauna becomes the dominant oxygen sink. Further the study investigated the effect of varying organic content on oxygen distribution and consumption dynamics. Immature waste bodies were observed to produce highly variable oxygen consumption and distribution due to unpredictable microfauna proliferation. Increasing organic content elevates oxygen consumption but the increased consumption is not proportional to the increase in organic availability. These factors suggest that the oxygen consumption rate in immature, highly organic, waste is not simply predicted based solely on time. It may be acceptable to assign a generalized, fixed rate of oxygen consumption for landfills rich in organics matter.*

Index Terms— *aerobic biodegradation, solid waste, organic waste, oxygen consumption*

I. INTRODUCTION

According to the World Bank, in developing countries in Latin America and the Caribbean (LAC), as much as 95% waste generated in these countries is treated by some form of in-situ land disposal on a spectrum ranging from planned sanitary landfills to ad hoc open dump sites [1]. Regardless of the location or condition of these disposal sites, they share an important characteristic; as much as 70% of the waste they contain can be considered as some form of easily degradable organic matter (kitchen waste, paper products, wood). With the high organic composition of the wastes of these landfills the introduction of oxygen into these waste bodies is expected to greatly accelerate the stabilization of these sites. While there has been research into understanding the mechanisms affecting the influx of oxygen into soils [2],[3],[4], the research has been primarily focused the role of flora on oxygen demand. Landfills in LAC and other developing regions pose a different facet to the soils in these studies due to the expected difference in organic concentration. Studies on understanding and modelling the transport and consumption of oxygen specifically within waste bodies has been previously undertaken [5],[6]. These studies demonstrated the link between oxygen consumption and oxygen diffusion into solid waste. However, the conditions replicated mirrored that of the present municipal solid waste of a developed nation composed predominantly of incineration residues. This waste composition does not reflect the waste composition of the developing world. To understand the oxygen dynamics of

organic waste additional work is required. The aim of the current research is to focus on waste of high organic content. Column experiments were performed to analyze the oxygen profile of highly organic waste and the associated oxygen consumption rate.

II. MATERIALS AND METHODOLOGY

A. Samples

Proxy materials were utilized to represent the target waste stream. Easily degradable organic matter in the form of compost (CP) generated from food waste was selected as the organic fraction as it was deemed a close approximate to the kitchen waste. The inorganic and not easily degraded fraction of waste was replicated utilizing waste incineration bottom ash (BA) sieved for the fraction under 10mm then air dried before use.

B. Materials

Figure 1 shows the layout of the materials utilized for the study. The columns used were composed of acrylic material of dimensions 0.1m (Diameter)x 2m (Height) consisting of two layers; a. Drainage layer, b. Waste Layer.

The drainage layer consisted of glass beads to facilitate separation and removal of leachate from the waste mass. The waste layer spanned a depth of 187cm and was constructed utilizing CP and BA. BA and CP were subjected to analysis including particle size distribution, moisture content (ω [%]), ignition loss [LOI (mg [g-dry solid (DS)]), oxygen consumption and leachability

characteristics. The methodologies utilized for these analyses were referenced from [5]. A total of three (3) columns were constructed with the proportions of 0%CP:100%BA in column 1; 10%CP:90%BA in column 2 and 20%CP:80% BA in column 3. The mixture was placed into the columns in 10cm layers at a time to ensure uniform compaction to an average density of approximately 1100 kg/m³. The columns were purged of oxygen by opening all ports and applying a positive pressure of pure nitrogen gas (N₂) to displace oxygen. The addition of Nitrogen was terminated and all ports and openings, including the leachate collection port, closed and the baseline oxygen levels determined. Once baseline levels were obtained, the top of each column was opened to allow unrestricted gas exchange.

C. Sampling

Closed gas sampling ports were established at every 0.1m height intervals for the first meter of the column and subsequently at 0.2m intervals for the remaining meter for

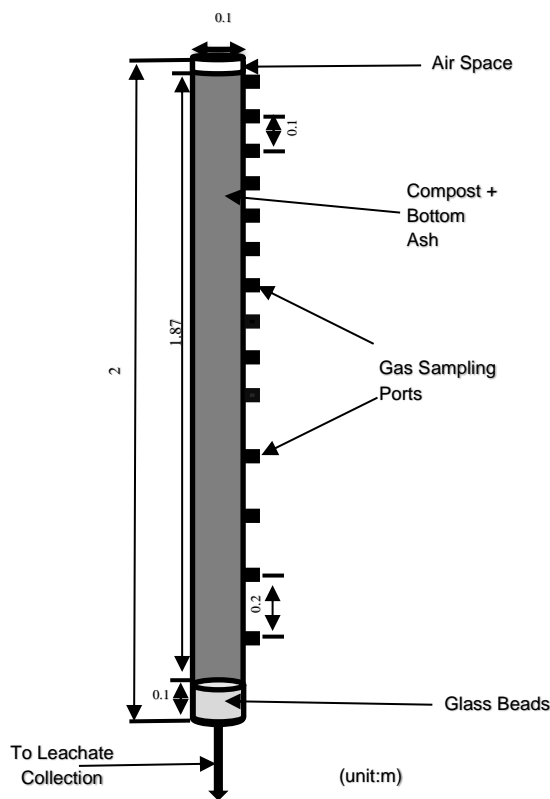


Figure 1: Column Layout

a total of fourteen (14) points. Each sampling port was protected by a ball valve. The mouth of each valve was sealed by a plastic sleeve and capped with a rubber cork to isolate the sampling ports from the outside air, when the samples were being removed. Samples were removed utilizing a needle affixed to a 6ml syringe via a 3-way stopcock. Before samples were taken the residual air within each sample port was first withdrawn utilizing the

syringe to create a vacuum within the sample port. The needle was then reinserted into the vacuum before the valve was opened. The air within the cavity was then mixed by pumping the syringe repeatedly approximately 10 times. A sample, not exceeding 2-3ml was extracted and kept for analysis utilizing a SHIMADZU GC-2014. Gas samples were obtained from the column initially every two days for the first week, after which they were taken at 5–7-day intervals.

Leachate was collected via collection bottles attached to the column via hoses. When leachate was not being collected, the hoses were sealed to prevent gas entering the column. A leachate head was maintained within the collection system to prevent entry of air when leachate was collected. Leachate was removed on an as needed basis as the drainage layer approached capacity. Collected leachate was recirculated back into the columns.

Moisture was supplied to the columns initially in the form of distilled water at a rate of 40ml per day to simulate an average daily rainfall of 5mm, typical of tropical climates.

III. RESULTS

A. Waste Characteristics

Table I- Loss on Ignition Test

	Moisture Content (%)	Loss on Ignition (%)
BA	11.88	0.78
CP	11.37	60

Table II-Leaching Test Analysis

COLUMN	TOC (mg/L)	IC (mg/L)	TC (mg/L)	TN (mg/L)
(0%CP: 100%BA)	19.70	N.D	19.7	3.20
(10%CP: 90%BA)	383.3	0.6	383.9	49.9
(20%CP: 80%BA)	1411	7.0	1418	178

(N.D – Not Detectable)

Tables I-II show results of analysis undertaken on the waste materials utilized. The CP utilized as the organic fraction contained around 60% volatile organics based on loss on ignition tests (I). BA utilized contained less than 1% volatile organic matter. Leaching tests (II) further

demonstrate the low levels of readily available carbon available in BA as compared the elevated levels in CP.

B. Oxygen Distribution

Figures 2-4 present the oxygen distribution profiles for the experiment. The first graphic (a) maps the oxygen concentration measured at each sampling point (vertical axis) vs time (horizontal axis). The oxygen concentration at the intervals which were not measured were interpolated based on the measured data. Blue represents areas of low oxygen concentration with red representing atmospheric concentration. Graphic (b) represents the change in oxygen concentration (vertical axis) with time (horizontal axis) at selected sampling ports. Graphic (c) highlights the vertical oxygen distribution within the column on selected days. After air was introduced, it rapidly diffused to the lower levels driven by the large diffusion gradient between the atmosphere and the waste mass created by the oxygen purging at the start of the experiment. In pure BA oxygen penetrates slowly and continuously driven primarily by the diffusion gradient with resistance to the diffusive movement defined by the diffusion coefficient of oxygen in BA. Within 100 days the diffusion gradient became minimal with no significant difference in oxygen levels between the column surface and the base. In the presence of organic matter the effect on the oxygen profile is readily observed. After initial replenishment of the oxygen concentration to the 12-14% range the subsequent 30 days saw the oxygen levels in both columns begin to decrease. The reduction in oxygen in the columns with high organic matter as opposed to no reduction in bottom ash was thus attributed to oxygen consumption from bacterial respiration utilizing the available substrates. The oxygen distribution profile of organic waste however produced an irregular structure where the oxygen consumption appeared adhoc and oxygen concentration was not linearly distributed as observed in bottom ash. This was attributed to the tendency of microorganisms in soils, even though being present at 10^6 - 10^{12} individual cells per gram of soil, to mainly associate into colonies which in turn develop into respiration hotspots.[7]. These hotspots are defined as small pockets within the soil which display accelerated microbial process as compared to the surrounding areas[8]. These hotspots become active during what are termed hot moments; triggers which spur microorganisms moment. Bearing similar characteristics to soils, the waste mass was believed to be subject to a similar process. One dominant factor which is proposed as the catalyst for the promulgation of the hot moments observed in the simulated waste mass was temperature. Due to the columns being composed of acrylic material into action. As such the introduction of any factor, which previously limited microbial growth, can trigger a hot

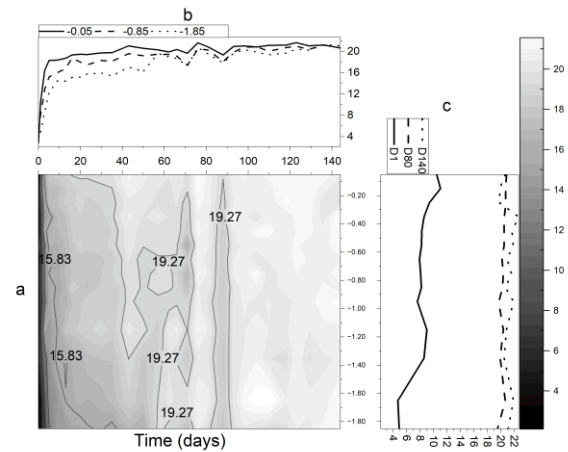


Figure 2: Oxygen Distribution 100%BA

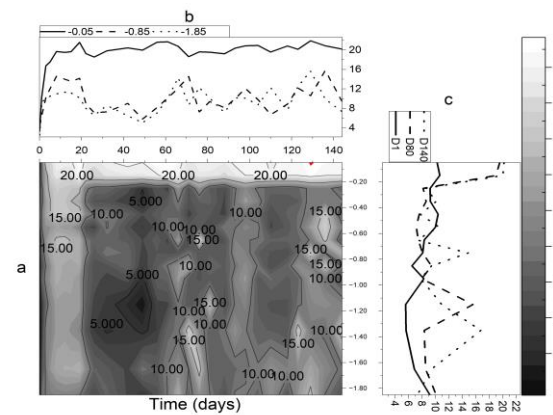


Figure 3: Oxygen Distribution 90%BA: 10%CP

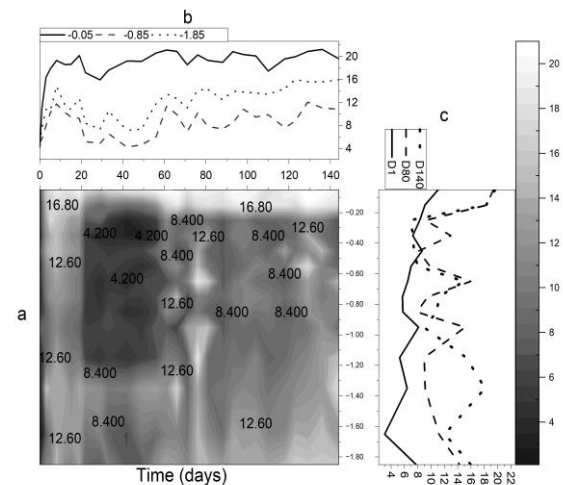


Figure 4: Oxygen Distribution 80%BA: 20%CP

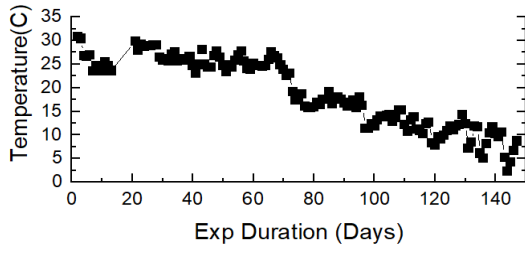


Figure 5: Atmospheric Temperature during experiment

there was no thermal insulation and as such the column temperatures were influenced by the external conditions. When the atmospheric temperature is considered, as seen in figure 5, a 5°C rise in temperature was observed between days 10 – 21. This temperature increase coincided with the observed hotspots in figures 3a+4a. With the subsequent reduction in the atmospheric temperature consistently below 25°C, after 70 days it was observed that, while some hotspots re-emerge their expanse and duration were reduced. The presence of temperatures above 25°C were therefore interpreted as being a common factor impacting the oxygen profile in organic waste due to its importance in promoting microbial activity.

C. Oxygen consumption

From the oxygen distribution profiles the greatest oxygen debt, post column opening, was observed with 20%CP where the minimum oxygen level recorded was as low as 4.3%. However, this value is not significantly lower than the minimum recorded in the presence of 10% CP of 4.7%. Initial high oxygen consumption in low oxygen soils has been shown to be initially driven by oxidation of ions into oxides e.g. Fe_2^+ , NH_4^+ combined with consumption by soil microorganisms [9]. The low oxygen levels observed with 10% CP and 20% CP after 20 days compared to the absence of additional organic matter shows the significant role of microorganisms in the consumption of oxygen in waste containing readily available substrates. Four separate areas, spanning the expanse of the columns, were selected as the points for the determination of maximal oxygen consumption rate. The rate was calculated utilizing the Crank–Nicolson form of the diffusion differential equation as referenced from [6]

$$\frac{(x)_k^{t+\Delta t} - (x)_k^t}{\Delta t} = \frac{1}{2} \frac{D}{\xi} \left(\frac{(x)_{k-1}^t - 2(x)_k^t + (x)_{k+1}^t}{\Delta y^2} + \frac{(x)_{k-1}^{t+\Delta t} - 2(x)_k^{t+\Delta t} + (x)_{k+1}^{t+\Delta t}}{\Delta y^2} \right) - \rho_d \frac{RT}{\epsilon P} R_1^t \quad (1)$$

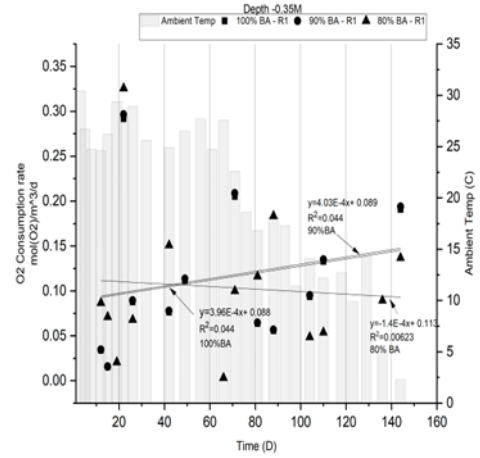


Figure 6: Calculated Oxygen Consumption Rate(-0.35M)

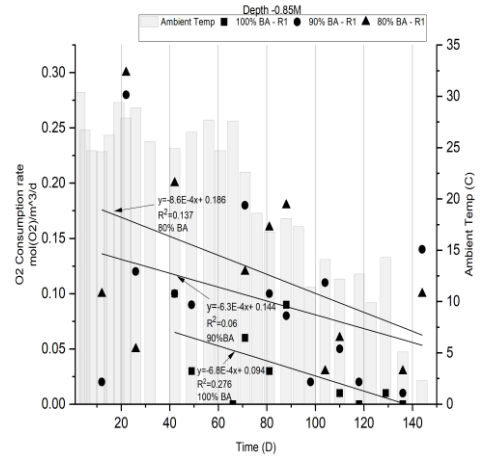


Figure 5: Calculated Oxygen Consumption Rate(-0.85M)

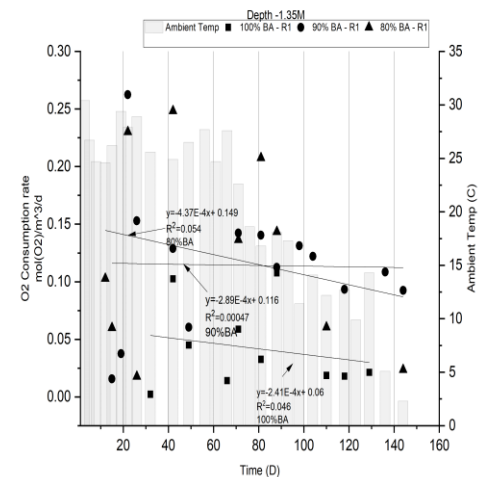


Figure 7: Calculated Oxygen Consumption Rate(-1.35M)

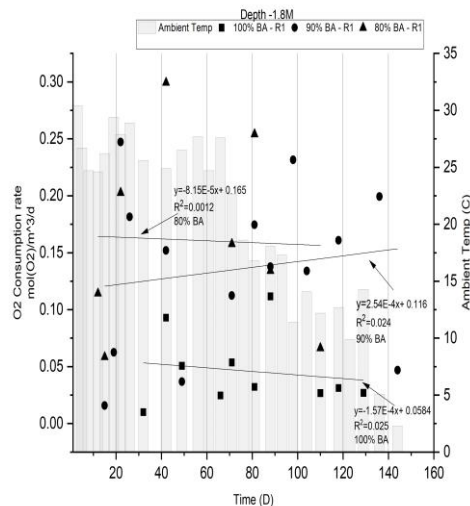


Figure 8: Calculated Oxygen Consumption Rate(-1.8M)

Where x is measured oxygen mole fraction (–), t is elapsed experimental time (days), k is sampling depth (m), D is the diffusion coefficient of oxygen (m^2/day), ξ is tortuosity(–), y is the distance between sampling points(m), P is the total pressure (Pa), R is the universal gas constant ($\text{m}^3 \text{ Pa mol}^{-1} \text{ K}^{-1}$), ρ_d is the dry density T is temperature (K) and R_1 is the oxygen consumption rate. Due to the discontinuity of the data, interpolation was conducted so that $y=0.1\text{m}$. Utilizing the Crank–Nicolson equation on this dataset resulted in days where there was no calculated positive oxygen consumption. Only days where net oxygen consumption was positive, were plotted and presented in Figures 6-9. These figures show the change in the calculated oxygen consumption rate with time with the first figure representing the consumption profile close to the soil-atmosphere boundary at -0.35m depth with the last figure representing the consumption at the deepest point. In terms of the depth calculated consumption rates determined at the hotspot near to the 0.85M displayed the clearest trend in all columns with highest consumption occurring during the initial periods with a gradual decrease with time. This trend was consistent to that observed in [5] in previously landfilled wastes. However, this trend was not clearly discernable at each depth analyzed. In terms of the time the high scatter of the calculated oxygen consumption rates as well as low predictability of the consumption rate with time given by the low R^2 values of the line functions derived further demonstrate the highly variable nature of oxygen consumption in organic waste in the near term. Longer term investigations are thus needed to determine the oxygen consumption function of highly organic waste.

IV. CONCLUSION

Landfills are by their nature very heterogeneous masses, and this is reflected in the tendency of respiration hotspots developing. These areas are characterized as

‘pockets’ where oxygen is utilized at accelerated rates compared to the surrounding areas due to favorable conditions being present for bacterial proliferation. This results in a variable oxygen profile where the oxygen concentration, at any given depth, is not simply and accurately predicted as a function of time in the short term. It may be therefore more applicable to utilize generalized consumption rates for mature and stabilized wastes with high organic content to account for hotspot activity in areas with subsurface temperatures averaging above 20°C . Further experimentation over an extended period at constant temperatures is recommended to create a general oxygen consumption function for organic wastes.

REFERENCES

- [1] Silpa, K., Yao, L. C., Bhada-Tata, P., & Van Woerden, F. (2018). What a Waste : Global Snapshot To 2050. Washington: World Bank Publications.
- [2] Cook, F. J. (1995). One-dimensional oxygen diffusion into soil with exponential respiration: analytical and numerical solutions. *Ecological Modelling*, 78(3), 277–283. [https://doi.org/10.1016/0304-3800\(94\)00179-L](https://doi.org/10.1016/0304-3800(94)00179-L)
- [3] Cook, F. J., & Knight, J. H. (2003). Oxygen transport to plant roots: Modeling for physical understanding of soil aeration. *Soil Science Society of America Journal*, 67(1), 20–31. <https://doi.org/10.2136/sssaj2003.2000>
- [4] Neira, J., Ortiz, M., Morales, L., & Acevedo, E. (2015). Oxygen diffusion in soils: Understanding the factors and processes needed for modeling. *Chilean Journal of Agricultural Research*, 75(August), 35–44. <https://doi.org/10.4067/S0718-58392015000300005>
- [5] Kallel, A., Matsuto, T., & Tanaka, N. (2003). Determination of oxygen consumption for landfilled municipal solid wastes. *Waste Management and Research*, 21(4), 346–355. <https://doi.org/10.1177/0734242X0302100407>
- [6] Kallel, A., Tanaka, N., Tojo, Y., Matsuto, T., & Hanada, S. (2006). Oxygen intrusion into waste in old landfills of low organic content. *Waste Management and Research*, 24(3), 242–249. <https://doi.org/10.1177/0734242X06064209>
- [7] Schlüter, S., Zawallich, J., Vogel, H. J., & Dörsch, P. (2019). Physical constraints for respiration in microbial hotspots in soil and their importance for denitrification. *Biogeosciences*, 16(18), 3665–3675. <https://doi.org/10.5194/bg-16-3665-2019>
- [8] Kuzyakov, Y., & Blagodatskaya, E. (2015). Microbial hotspots and hot moments in soil: Concept & review. *Soil Biology and Biochemistry*, 83, 184–199. <https://doi.org/10.1016/j.soilbio.2015.01.025>
- [9] Reddy, K. R., Rao, P. S. C., & Patrick, W. H. (1980). Factors Influencing Oxygen Consumption Rates in Flooded Soils. *Soil Science Society of America Journal*, 44(4), 741–744. <https://doi.org/10.2136/sssaj1980.03615995004400040016x>
- [10] Esener, A. A., Roels, J. A., & Kossen, N. W. F. (1981). The influence of temperature on the maximum specific growth rate of *Klebsiella pneumoniae*. *Biotechnology and Bioengineering*, 23(6), 1401–1405. <https://doi.org/10.1002/bit.260230620>