Development of a Lipid-Modified Biochar Aeration Layer for Oxygen-Driven Modulation of Organic Waste Decomposition and Methanogenic Potential

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Methane generated during anaerobic decomposition is a major source of landfill greenhouse gas emissions. This study investigated the effect of oxygen availability on decomposition pathways and evaluated the Lipid-Modified Biochar Aeration Layer (LMBAL), a proposed landfill-cover system designed to enhance oxygen diffusion. Organic waste was decomposed under controlled conditions, and decomposition indicators were monitored over time. A theoretical Methane Generation Potential Index (MGPI) was developed to compare methane-generation potential across treatments. Results suggest that increased oxygen accessibility is associated with lower methane-generation potential and support further investigation of LMBAL as a methane-mitigation strategy.

Keywords: Landfill, landfill cover, methane generation potential, methanogenesis, microbial kinetics, organic waste decomposition, oxygen accessibility.

Introduction

Background and Context

The concentration of methane in the atmosphere is higher than it has been in at least 800,000 years[1]. Methane is a highly potent greenhouse gas that absorbs and re-emits thermal radiation, contributing to the greenhouse effect[2]. Emissions of methane persist, placing methane second, after carbon dioxide, for the most severe human-induced greenhouse gas[3]. Given the significant environmental impact of methane emissions, identifying major sources of methane production is essential.

Municipal solid waste landfills are the third largest source of human-related methane emissions in the U.S., ∼60% of which are the result of food waste[4]. This connection between landfill waste composition and methane production is particularly relevant to the present study. The amount of food waste in landfills is relevant to this study, as food waste is often organic waste, which is the type of waste measured in this study, and irregular decomposition conditions result in the emission of greenhouse gases.

To address the environmental consequences of landfill emissions, current waste management strategies focus on reducing the amount of organic material entering landfills. Current waste diversion methods involve reuse, recycling, or composting of waste with the intention of keeping waste out of landfills. For example, composting allows organic matter to be recycled through the carbon cycle as aerobic microorganisms break it down into soil amendments[5–8]. Microorganisms use organic matter as a source of energy and carbon for growth while breaking down its more readily decomposable components[9,10]. In contrast, when food and other organic materials decompose under anaerobic conditions in landfills, microbial activity generates methane, a potent greenhouse gas[6]. However, composting can also release greenhouse gases, including methane and carbon dioxide, with emissions varying according to the composting method and the composition of the organic material[11,12].

However, while these methods provide alternatives to landfill disposal, they do not fully resolve the challenges associated with controlling decomposition conditions. Despite these approaches, challenges remain in optimizing decomposition, highlighting the need for innovation. For instance, oxygen is quickly consumed during microbial activity, creating anoxic zones that would otherwise be considered aerobic[13]. This indicates that bulk oxygen conditions may not accurately represent microbial-scale reactions that may be happening anaerobically[13]. Additionally, Zhang et al. have shown that simulating realistic landfill compact environments allows for the consideration of gas diffusion limitations, waste heterogeneity, and anaerobic zone formation[14]. Therefore, developing experimental systems that accurately represent landfill con-

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ditions is critical for understanding microbial decomposition processes. To set up a realistic experimental landfill compact environment, these factors must be taken into consideration and accurately replicated under controlled laboratory conditions.

One approach to controlling decomposition conditions within landfill environments is the use of landfill covers, which regulate interactions between waste and the surrounding environment[14]. Landfill covers like biochar amended soil (BAS) and soil covers have been used independently to manage decomposition, but each method presents limitations that motivate the need for modifications. Soil covers meet requirements of cover material in landfill areas, but soil compaction and low gas permeability limit diffusion of gases, resulting in the formation of anaerobic zones under the cover[15,16]. Additionally, leachate, hazardous wastewater accumulates at the body of landfills. It contains toxic substances such as Ca^{2+}, Mg^{2+}, in large quantities[17]. Leachate may also runoff and contaminate groundwater and soil, disrupting terrestrial ecosystems and food chains[17].

BAS layers are layers of biochar mixed with soil and placed on landfills[18,19]. They prevent the ingress of water caused by rain, and have the potential for enhancing methane oxidation, converting methane into carbon dioxide, by increasing methane retention time[18]. Additionally, methanogenesis, the generation of methane by anaerobic microorganisms, could be used as a source of renewable biogas[19,20]. BAS layers stabilize anaerobic decomposition, removing volatile fatty acids and other toxic substances produced by microbial decomposition processes. While BAS layers have been widely studied, their ability to maintain consistent oxygen diffusion in compacted waste systems remains limited. LMBAL introduces a lipid modification to address structural limitations in preserving oxygen access in a landfill cover matrix. Therefore, modifications to existing landfill covers are necessary to improve oxygen accessibility and reduce the formation of anaerobic zones. The model proposed in this study introduces a lipid modification to address structural limitations in preserving oxygen access in a landfill environment.

Objectives

This study explores how waste diversion impacts decomposition conditions, by comparing how aerobic and anaerobic microbial decomposition affect the rate of organic matter degradation and associated indicators of anaerobic decomposition and a modeled methane generation potential (MGP).

Hypothesis

Research supports the prediction that aerobic conditions in decomposition will result in a larger mass loss. In contrast, organic material decomposing under anaerobic conditions will exhibit a higher modeled MGP because oxygen limitation promotes methanogenic microbial pathways. Environmental factors such as moisture and temperature also affect the degradation of organic matter[21,22]. Based on these factors, aerobic decomposition is expected to demonstrate characteristics associated with effective organic matter degradation. Qualities of aerobic decomposition include: Relatively neutral pH (7-8), stable temperatures which are closer to to the ambient temperature, brown in colour, arid in moisture, and soil-like in texture, and often has a weaker odour and visible mold formation[23,24]. These characteristics support the prediction that aerobic conditions promote greater decomposition and mass loss through increased microbial activity.

In contrast, anaerobic decomposition is expected to demonstrate characteristics associated with increased methane production due to oxygen limitation. Qualities of anaerobic decomposition include: Alkaline pH, because the breakdown of organic nitrogen and reactions of its products make the organic matter more alkaline, and could be harmful to the atmosphere if volatilized to a gas[23,25,26]. Additionally, anaerobic decomposition involves higher temperatures, especially in thermophilic ranges, because there is a positive correlation between temperature and emission rate[23]. Moreover, anaerobic zones often have a moisture content of 40-60% above the optimal range, as water acts as a physical barrier that restricts oxygen diffusion[23]. Anaerobic conditions are associated with more pungent odours generated by trapped compounds in the decomposing matter, such as ammonia, and form black precipitate caused by reactions of odorous compounds with minerals[23,27]. Lastly, anaerobic decomposition produced gases, which could accumulate on a liquid surface, appearing as brown foam[28,29]. Overall, aeration during decomposition maintains optimal biological activity and also is a critical parameter on methane emissions and other greenhouse gases[24].

Theoretical Framework and Methodology Review

This study is grounded in biogeochemical cycling theory, which examines how microbial processes regulate carbon cycling and organic matter decomposition[8,30,31].To investigate these processes, organic waste samples were placed under controlled aerobic and anaerobic conditions, where qualitative and quantitative indicators of decomposition were monitored regularly. A landfill-cover model (LMBAL) is proposed to mitigate methane generation. In addition, this study introduces a normalized Methane Generation Potential Index (MGPI), adapted from established methane-emission quantification principles, to compare relative methane-generating conditions among experimental groups.

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Proposed Model

Proposed Model

This study proposes a Lipid-Modified Biochar Aeration Layer (LMBAL). LMBAL is a hybrid, combining existing techniques with the goal of maintaining aerobic conditions, thus decreasing greenhouse gas production. It combines biochar-based absorption and porosity, lipid modifications, and passive aeration. Lipid modifications were added because lipids preserve channels for oxygen diffusion, preventing the formation of anaerobic zones[32]. Lipids also provide a high-energy carbon source which stimulates aerobic microbes, promoting growth and respiration[32]. LMBAL was tested in controlled landfill simulations to evaluate its performance compared to biochar-only covers, directly measuring the impact of proposed modifications.

Methods

Research Design

Aerobic vs Anaerobic Experiment

This study used a controlled experimental design to compare the effects of aerobic and anaerobic conditions on the decomposition of organic waste. Organic matter was placed in controlled anaerobic and aerobic growth chambers and monitored over a 14-day period, with measurements recorded routinely according to the sampling schedule. Temperature, moisture, odour intensity, texture, and colour were recorded daily. Due to limited laboratory access on weekends, mass was taken every other day, excluding weekends. This was done to keep trends linear, despite practical experimental constraints. This comparison was necessary to establish how oxygen availability influences decomposition pathways and provide a baseline for evaluating whether LMBAL promotes conditions associated with reduced methane generation potential. By establishing the differences between oxygen-accessible and oxygen-limited decomposition, this experiment provided the reference conditions needed to interpret the impact of LMBAL on decomposition characteristics.

Large-Scale Anaerobic Experiment

To model how waste behaves on a larger scale, supplemental containers were set up under anaerobic conditions, as larger-scale experiments more accurately resemble landfill conditions. These containers provide a simplified representation of landfill conditions. During the experiment, organic matter was added to a total of 50 containers. Temperature, moisture, and qualitative observations such as texture, colour, odour intensity, and mass, were monitored over this 10-day period. This experiment was included because landfill environments contain larger volumes of compacted organic material, and evaluating anaerobic decomposition at a larger scale allowed for comparison with characteristics expected in real landfill systems.

LMBAL Assessments

To test the efficiency of the proposed model, 2 experiments were conducted. These experiments were designed to directly evaluate whether the structural modifications introduced by LMBAL, including lipid modification and biochar concentration, influenced decomposition indicators associated with methane generation potential. The first experiment compared LMBAL model samples (biochar-wax cover and the cellulose filter paper) to samples with only biochar and cellulose, and control samples with the cellulose filter. The second experiment tested the impact of different biochar concentrations on oxygen diffusion and gas emissions, and consisted of the following four groups: A control group, with a cellulose filter and wax, a low biochar group with biochar and wax, a medium biochar group with biochar and wax, and a high biochar group with biochar and wax. Both groups were tested over a 10-day period, where odour intensity and mass were recorded every 24 hours. These LMBAL experiments were designed as preliminary proof-of-concept assessments to evaluate the feasibility of the proposed cover system rather than to provide definite comparisons. Small groups (2-3 samples per group) were used to identify large treatment effects and subsequent optimization. Therefore, the purpose of these experiments was to identify whether LMBAL produced measurable differences in decomposition conditions and determine factors requiring optimization before larger-scale testing.

Sample

The experimental samples for the aerobic vs. anaerobic experiment consisted of mixed organic waste, primarily composed of fruits and vegetables to simulate common household food waste found in municipal landfills; each container contained 38 ± 8g of organic matter. The experimental samples for the LMBAL experiments contained the same type of organic matter, and 90 ± 5g of organic matter. The large-scale anaerobic experiment also involved the same type of organic matter and contained 117 ± 5g of organic matter.

Data Collection

Data was collected routinely over the experimental period. Measurements and qualitative data records included mass loss, temperature, moisture, odour intensity, colour, and texture. Quantitative measurements were recorded according to the sampling schedule, while qualitative indicators were evaluated daily using standardized rubrics developed specifically

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for this study. The rubrics provided scoring criteria for each of the qualitative indicators to guarantee consistency in results. All qualitative records were taken by the same scorer to improve scoring accuracy. Because this data is considered partially subjective, these qualitative indicators were analyzed as semi-quantitative supporting values.

Variables and Measurements

Variables

For the aerobic vs. anaerobic experiment: The independent variable was oxygen availability. Dependent variables were mass loss, temperature, moisture, odour intensity, colour, texture, microbial growth, and modeled MGP (using the MGPI). Controlled variables were initial mass of organic waste, container side, light exposure, organic matter type, and measurement schedule. In the LMBAL experiments: The independent variable was the landfill cover, and dependent variables were mass, odour intensity, gas production, and microbial growth. Controlled variables included mass of organic matter, container size, and temperature. The large-scale anaerobic experiment has mass loss, temperature, moisture, odour intensity, colour, texture, gas production, and microbial growth as dependent variables. There were no independent variables, as this experiment was an extension of the anaerobic condition in the aerobic vs. anaerobic experiment. Lastly, controlled variables included container size, temperature, amount of organic matter, condition, light exposure, organic matter type.

Methane Generation Potential Index (MGPI)

This study introduces a normalized Methane Generation Potential Index (MGPI), rather than direct methane measurements, to compare the relative methane-generating potential of experimental groups. The MGPI is adapted from methane-emission principles described in a report by the Government of Quebec[33], which estimates methane emissions as proportional to the quantity of decomposing organic waste:

$$E_{\mathrm{CH_4}} = EF_{\mathrm{CH_4}} \times Q_{\mathrm{OWM}}$$

Because all experimental groups consisted of similar organic waste, the methane emission factor $EF_{\mathrm{CH_4}}$ was assumed constant across treatments. Therefore, differences in methane generation potential were assumed to depend primarily on the amount of organic matter undergoing decomposition.To create a dimensionless comparison suitable for laboratory-scale experiments, MGP was normalized using:

$$MGPI_i = \frac{\Delta M_i}{\Delta M_{\max}}$$

In this equation; MGPI is the Methane Generation Potential Index, which ranges from 0-1; ΔM_i is the mass loss of the experimental group; $\Delta M_{\max}$ is the greatest mass loss observed across all groups. Larger MGPI values indicate greater theoretical MGP assuming identical waste composition and decomposition conditions.

Procedure

Aerobic vs Anaerobic Experiment

In the main experiment, containers were filled with 38 ± 8g of organic matter and divided into aerobic and anaerobic conditions. Aerobic containers were left open to allow oxygen diffusion, while anaerobic containers were closed with airtight seals to restrict oxygen access. Temperature, odour intensity, moisture, texture, and colour were taken daily, while mass was taken every 48 hours. Samples were then plated for microbial analyses and microscopies. This experiment was the primary comparative experiment for hypothesis testing.

Large-scale anaerobic experiment

During the large-scale anaerobic experiment, a total of 50 containers ($18.3 \times 12.2 \times 9.7$ cm), per condition, were filled with 117 ± 5g of organic matter, such as fruits and vegetables. Containers were stored indoors at ambient room temperature, which fluctuated slightly between 17-19 °C, and exposed to approximately 10-12 hours of light each day, simulating outdoor light exposure. Temperature, moisture, and qualitative observations such as texture, colour, and odour were taken in 24-hour intervals over a ten-day period using a rubric, while mass was taken every 48 hours. Anaerobic containers were closed and sealed in opaque bags, acting as a secondary barrier to oxygen exposure.

LMBAL experiments

"Covers" for the first LMBAL experiment were prepared the following way: the cellulose filter for every group was a circular qualitative cellulose filter with a diameter of 4in, and was placed over the organic matter in each container. The biochar-cellulose group had the cellulose filter, along with 4g biochar placed between the filter and the organic matter. Lastly, the LMBAL models were prepared using 30g melted beeswax lightly brushed onto the biochar that is on the cellulose filter. The cellulose filter was allowed to dry and the LMBAL cover was placed upside-down over the organic matter, with the filter on top, and the wax and biochar directly on the decomposing material. The LMBAL cover was 1in high, with a 4in diameter.

The second experiment used a LMBAL-type cover for every experimental group; the control had a LMBAL cover with no biochar, but with wax and the cellulose filter; the low-biochar group had 4g of biochar, and also had the controlled amount of wax (30g), as well as the filter; the medium-biochar had the same conditions, but with 8g of biochar; the high-biochar group had 12g biochar. All covers were 4in in diameter and

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placed upside-down on the organic matter in the container. LMBAL was tested under controlled laboratory conditions over a 10-day period. The control samples with only a cellulose filter were C1 and C2; biochar and filter samples were CB1 and CB2, and lipid-biochar filter samples were L1 and L2. Mass and odour intensity were taken daily as quantitative and qualitative observations.

Data Analysis and Ethical Considerations

Mass measurements were used to calculate decomposition rates, average mass loss over time, and estimate relative MGP using the MGPI framework. Moisture was taken as an additional parameter in microbial decomposition. Observational data, including odour intensity, colour, and texture, were qualitatively compared between aerobic and anaerobic decomposition. No human or animal subjects were involved in this study. Organic waste materials were handled safely and disposed of according to local waste guidelines.

Results

Primary LMBAL Assessment

During the primary LMBAL assessment, C1 and C2 exhibited the highest mass loss, 30g and 23g, corresponding to decomposition rates of 32.4% and 25.6% (2.94 ± 0.93g/day, $n = 2$). L1 and L2 had the lowest mass loss (13.5 ± 3.54g, $n = 2$), with decomposition rates of 18.0% and 12.3% (1.32 ± 0.0676 g/day, $n = 2$). Lower mass loss rates suggest that decomposition, and thus suggesting gas production was slower in LMBAL samples. Mass loss trends are consistent with decomposition occurring under oxygen-available conditions. Odour observations show that LMBAL samples had the least odour, the CB samples had an intermediate odour level, and control samples had the most odour. These odour strengths correlate positively to the decomposition rates and indicate the innovation limits emissions of odourous gases.

Biochar-Gradient LMBAL Assessment

The control samples had the highest decomposition rate during the biochar gradient LMBAL assessment, corresponding to decomposition rates of 28.2%, 22.4%, and 32.4% (2.81 ± 0.5g/day, $n = 3$). The other three experimental groups had very similar mean decomposition rates, 14.3% (1.59 ± 0.25g/day, $n = 3$), 13.7% (1.52 ± 0.20g/day, $n = 3$), and 13.3% (1.48 ± 0.35g/day, $n = 3$), with the lowest decomposition rate belonging to the high biochar concentration samples. The control group's odour intensity progressively rose from 1 to 4 over the experimental period, while the odour intensity of the experimental groups only rose to 2.

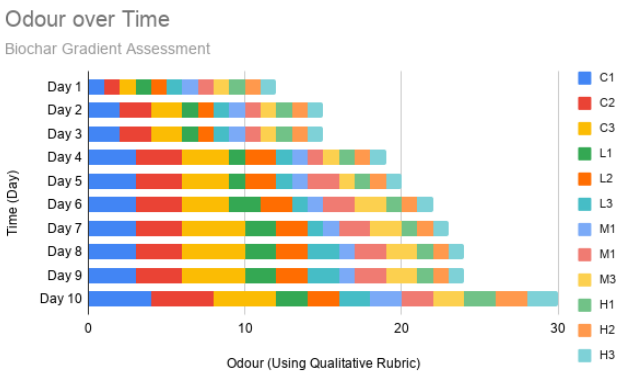

Figure. 1 Odour Intensity over Time for Biochar Gradient Assessment Experiment, overview of odour (rubric-based) over time, 4 groups with 3 samples per group (as seen in the legend on the right side of the figure), figure shows stacked odour values to show collective increase in moisture for samples over time, with moisture differences depending on experimental group.

The calculated MGPI followed the same trend as decomposition. The control group had the highest normalized MGP (MGPI = 1.00), while the experimental groups showed substantially lower values: low-biochar (MGPI = 0.57), medium-biochar (MGPI = 0.54), and high-biochar (MGPI = 0.53). The similarity among the biochar treatments suggests that increasing the biochar content beyond 4 g (approximately 4.2-4.7% of the total organic mass) provided little additional reduction in theoretical MGP.

Large-Scale Anaerobic Decomposition Experiment

Over time, colour, texture, and odour observations increased from 1 to 4 over the experimental period (rubric-based comparison), indicating that as anaerobic organic matter is further along the decomposition process, odour intensity, darkening, and compressibility increases. The largest moisture increase occurred between days 8-10, indicating accelerated moisture increases during later stages of anaerobic decomposition. Room temperature fluctuated between 17-20 °C. Mean container temperatures rose above ambient temperature from days 2-4. After this peak, mean container temperatures dropped below room temperature for the remainder of the experiment.

Containers that experienced greater mass loss exhibited higher MGPI values, suggesting greater theoretical MGP.

Aerobic vs. Anaerobic Decomposition Experiment

Decomposition rates of the aerobic samples ranged from 31.6-67.7% (4.63 ± 0.79g/day, $n = 12$), while anaerobic decompo-

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Table 1 Procedure Overview

Experiment	Purpose	Conditions/groups	n	Duration	Variables
Large-scale anaerobic	Check consistency of anaerobic characteristics	Sealed (anaerobic)	50	10 days	Mass, odour, moisture, texture, colour, temperature, MGPI
Aerobic vs anaerobic	Baseline comparison	Sealed, open	12/group	14 days	Mass, odour, moisture, texture, colour, temperature, MGPI
LMBAL test	Cover efficiency	3 groups: C (control), CB (biochar), L (LMBAL model)	2/group	10 days	Mass, odor, MGPI
Biochar gradient	Optimization	4 biochar conc. Groups: C (none/control), L (low), M (medium), H (high)	3/group	10 days	Mass, odour, MGPI

Table 2 Qualitative Rubric used for Anaerobic vs. Aerobic Decomposition experiment and Large-Scale Anaerobic Experiment

Trait	**Minimal (1pt)**	**Slight (2pts)**	**Moderate (3pts)**	**Significant (4)**
Texture	Surface mostly form, no mushiness	Slight softening in some areas	Noticeably soft or crumbly in some parts	Very soft, slimy, or breaking apart easily
Smell	No noticeable odour	Faint, barely noticeable odour	Noticeable odour, slightly unpleasant	Strong odour, distinctly unpleasant
Colour	Original colour	Slight darkening or dulling	Noticeable darkening or spots forming	Significant darkening, black/brown patches or mold
Moisture	Very dry, crumbly (0-1)	Slightly dry, just a bit damp (1.5-3)	Moist, feels soft to touch (3.5-6)	Very wet, soggy or dripping (6.5-10)

sition rates ranged from 0.00% to 3.33% (0.13 ± 4.71g/day, $n = 12$).

Moisture remained constant in the aerobic decomposition samples with 11/12 samples having a moisture level of 1, and one sample having a moisture level of 2. Anaerobic samples had varying moisture levels, with the average moisture being 4.2 on the last day of the experimental period. The temperature of the organic matter under aerobic conditions was higher than room temperature from days 2-6, at the start of the experimental period, indicating a peak in microbial activity. In contrast, the temperature of organic matter under anaerobic conditions was only higher than room temperature on day 9, near the end of the experimental period. Colour and texture in both aerobic and anaerobic conditions began at 1-3 at the start of the experimental period and progressed to 4 in every sample by day 14 (rubric based). Odour intensity for organic matter undergoing aerobic decomposition was a constant 2, with a soil-like smell, while every sample of organic matter undergoing anaerobic decomposition began the experiment with an odour intensity of 2, and had an odour intensity of 4 by day 14. Overall, decomposition trends for aerobic decomposition tend to be stable, while those for anaerobic decomposition tend to fluctuate or progress.

Discussion

The results show clear differences between aerobic and anaerobic decomposition. Aerobic samples decomposed significantly faster, had low moisture content, and maintained a low odour, while anaerobic samples decomposed very slowly and often gained weight, had high moisture content, and had very high odour intensities.

The LMBAL treatment reduced both decomposition rates and odour intensities while maintaining aerobic conditions. Aerobic environments were associated with higher decompo-

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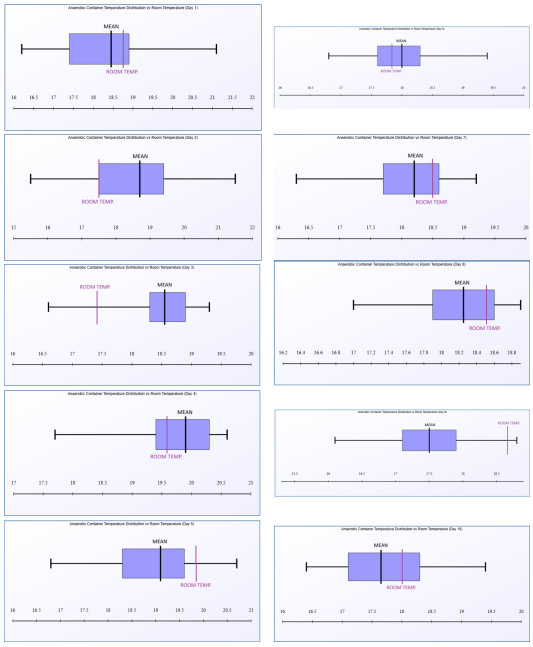

Figure. 2 Mean Temperature of 50 samples in Large-Scale Anaerobic Decomposition Samples During Experiment, temperature measured in degrees celsius.

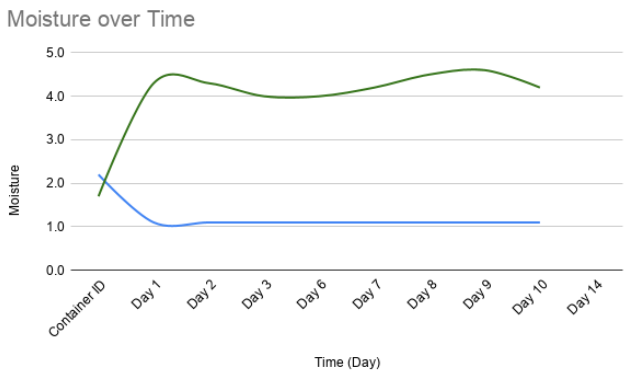

Figure. 3 Moisture vs. Time for Anaerobic Decomposition, Quantitative, sensor-based (1-10), experimental and control groups of 12 samples. The green graph is the anaerobic average moisture, and the blue graph is the aerobic average moisture.

sition rates across all experiments. These patterns can be explained by oxygen availability's effect on microbial activity. In aerobic conditions, microbes break down organic matter effectively through oxygen-dependent pathways, leading to rapid decomposition and fewer harmful byproducts. In contrast, oxygen-limited environments favour anaerobic decomposition, which is associated with higher MGPI values and increased formation of anaerobic decomposition by-products.

The effectiveness of LMBAL suggests it creates aerobic zones in organic matter. However, adding biochar beyond 4.2-4.7% of the total mass of the organic sample would be a setback financially and impeding timewise, due to its insignificant impacts. Therefore, the optimal version of LMBAL should contain 4.2-4.7% of the total mass of the organic sample. This study involves practical significance through testing of the proposed model, as well as theoretical understanding that oxygen availability is the key driver of decomposition pathways.

Connection to Objectives

The primary objective of this study was to investigate how oxygen availability affects microbial decomposition and methane production potential in organic waste. The results mostly supported the hypothesis. As expected, anaerobic conditions exhibited higher MGPI values than aerobic conditions, indicating conditions theoretically more favourable for methane generation, confirming that oxygen limitation increases methanogenesis. However, the data also revealed an unexpected pattern: The rate of decomposition was slower than predicted, suggesting that factors beyond oxygen accessibility influence decomposition, such as moisture content. These outcomes highlight the importance of considering multiple ambiental factors when monitoring decomposition characteristics.

Limitations

Each container was at a slightly different stage of decomposition, potentially introducing variability in measurements, as it is difficult to determine the exact decomposition stage of each piece of organic matter (each vegetable piece) in the experiment. While this limitation may have affected the results, it simulates real-world conditions, making findings relevant to landfill decomposition conditions. Additionally, the system tested is a small-container decomposition study, not a landfill simulation. This study was conducted as a primary analysis of decomposition conditions, with a proposed prototype, but the following should be considered if the prototype is to be improved or studied in the future: The system does not account for landfill compaction, durability, or long-term field performance. Although standardized rubrics were developed and used consistently through the experiment, qualitative records remain subject to observer bias. Future studies should incorporate multiple observers or blinded scoring procedures. Oxygen-diffusion comparisons were based on aerobic vs. aerobic decomposition qualities rather than direct oxygen measurements. Future studies should involve oxygen sensors or quantification of oxygen presence and movement. Methane

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concentrations were not directly measured using gas sensors or gas chromatography. The MGPI is a theoretical comparative framework derived from decomposition characteristics and established methane-generation principles and therefore should not be interpreted as a direct quantification of methane emissions. Future work should validate the index against measured CH_4 concentrations under controlled landfill conditions.

Closing Thoughts

Future research should explore scaling the LMBAL, providing insight on its performance in real-world landfill conditions over longer periods of time. The proposed model should only be considered as a prototype or suggestion. If looking to develop it further, biochar could be sourced from post forest-fire biomass, repurposing the organic matter left over from these disasters. Selection of biochar may involve a rubric, or another means of assessing quality, and therefore efficiency in creating aerobic zones in a landfill. Additionally, alternative wax, preferably plant-based or synthetic, could be explored as a substitute for beeswax, reducing the impact on pollinators while maintaining LMBAL's performance.

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