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The Sustainable Treatment of Municipal Landfill Leachate

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Abstract -. In this study, cattle manure was co-digested with different ratios of landfill leachate: 75:25 (R1), 50:50 (R2), and 25:75 (R3) to evaluate the performance capacities of biogas, CH_4 production, and the volume obtained from this gas. The methane (CH_4) and carbon dioxide (CO_2) composition was analyzed using gas chromatography. A positive effect of leachate on methane production was observed in all three treatments when co-digested with cattle manure. It is evident that the highest methane production (CH_4) was achieved in R3, reaching values of 96.81% on day 36, while R1 had the lowest methane production with maximum values of 91.74% on day 16. These high methane values in all three treatments can be attributed to the synergistic effect of the mixture, where it is considered that aged leachate has a higher buffering capacity as well as a more acclimated methanogenic consortium, leading to rapid methanogenesis of the organic load. Finally, there is concordance between the volume of biogas generated in R3 and the maximum methane content achieved by the 0.3:1 ratio of landfill leachate and cattle manure used in this reactor. Likewise, the Duncan test applied to the daily volume generated in reactor 3 confirms the maximum biogas volume obtained in this experimentation with a value of 203.67 mL reached on day 16 of anaerobic co-digestion, with 95% reliability. This allows inferring a high potential for the utilization of leachate in circular economy initiatives to address the challenges of achieving sustainability in the efficient management of municipal urban waste.

***Keywords*:** Bioreactor; anaerobic; co-digestion; cattle manure; bioenergy.

1. Introduction

At a global level, the average annual generation rate of municipal solid waste (MSW) is 2.02 billion metric tons. Countries like Denmark (845 kg), the United States (811 kg), and solid waste production ranges from 0.11 to 4.54 kg per capita per day worldwide [1]. Although landfills are intended to protect humans and the environment from the harmful effects of waste, open dumps/landfills, due to their unengineered nature, pose a serious threat to the environment and human health [2].

Municipal solid waste (MSW) in open landfills is compacted, pressurized, and left unmanaged, resulting in a large quantity of leachate, mainly composed of suspended particles, soluble organic and inorganic compounds. Leachate is a highly toxic liquid that is regularly generated in landfills and poses a serious threat to the natural environment and ecosystem [3]. The main environmental effects of landfill leachate are attributed to the pollution of surface water and groundwater due to high concentrations of biodegradable organic matter, ammoniacal nitrogen, xenobiotic compounds, and heavy metals [4]. The composition of leachate depends on the characteristics and age of MSW, the chemical and biological degradation process, site hydrology, compaction of MSW, and climatic factors such as temperature and annual precipitation rate [5]. Young leachate has a biochemical oxygen demand/chemical oxygen demand (BOD_5/COD) ratio of 0.4 to 0.6. With organic degradation, the biodegradability of leachate decreases, and stabilized leachate is obtained from the landfill, known as mature landfill leachate [6]. Therefore, its treatment remains a social, environmental, and economic challenge for integrated municipal solid waste management [7]. Consequently, the intentional utilization of landfill leachate for bioenergy and the recovery of value-added chemicals through non-thermal biological methods, such as anaerobic digestion (AD), could be a suitable option to address the leachate disposal issue [8].

The inadequate management of municipal solid waste (MSW) in developing countries through open dumping, coupled with the growing problem of climate change attributed to methane emissions, as well as the adverse effects on humans consuming groundwater contaminated with leachate, calls for significant efforts to mitigate climate change and the pollution caused by unengineered landfills. However, there has been a recent paradigm shift in waste management, treating waste as a resource rather than a burden. In order to utilize landfill leachate (LL) effectively for bioenergy/energy production, technologies such as fermentation, anaerobic digestion (AD), supercritical water gasification (SCWG), and bioelectrochemical systems appear to be promising options. Additionally, to enhance the global efficiency of leachate utilization, potential technologies are being integrated through the coupling of biotransformation, dark fermentation, anaerobic digestion, and bioelectrochemical systems [2].

The demand for renewable and sustainable energy production has become an increasingly urgent concern worldwide due to advanced climate change and global warming [9]. To meet this demand, biogas from anaerobic digestion (AD) has been evaluated as one of the promising pathways for renewable bioenergy production [10]. Various wastes including agricultural residues, manure, slaughterhouse waste, organic fraction of municipal solid waste, and sewage sludge are amenable to anaerobic digestion, but face several limitations such as high solids content, low carbon-to-nitrogen (C/N) ratio, heterogeneity, inhibition, and instability issues due to the accumulation of ammonia and volatile fatty acids (VFAs) [11]. Biological treatment methods, especially anaerobic reactors, have been widely employed for landfill leachate treatment due to significant environmental and economic benefits over aerobic treatment, such as suitability for high organic loading rates, biogas generation potential, low sludge production, lower energy requirements, and reduced CO_2 emissions [12].

Furthermore, through anaerobic digestion, the organic matter in landfill leachate is biochemically converted into energy-rich carriers (methane and hydrogen), which can be utilized for heat production, electricity generation, and as fuel for combustion engines. In the anaerobic treatment system, influent containing a low concentration of biodegradable organic compounds results in low biogas abundance, whereas high organic loading rates (OLR) lead to the accumulation of VFAs in the system and deteriorate overall digester performance. Diverse microbial communities develop within anaerobic digestion systems during landfill leachate treatment, owing to the complex and variable composition of leachate. The abundance and richness of anaerobes are highly influenced by substrate composition, affecting the biodegradation of organic compounds, nitrogen removal, bioenergy production, and toxicity reduction. During the acidogenesis stage of anaerobic digestion, a significant volume of hydrogen is produced, which increases the hydrogen partial pressure and negatively affects the acidogenesis process. The presence of sufficient hydrogenotrophic methanogens alleviates this condition by utilizing the hydrogen generated during acidogenesis, establishing a syntrophic relationship with fermentative bacteria. Furthermore, efficient biodegradation of organic compounds and methane production rely on electron transfer between fermentative bacterial species and methanogens [13]. This research aimed to evaluate the performance capacities of biogas production, methane (CH_4) percentage, and the volume obtained from this gas over time through anaerobic co-digestion using cattle manure with different quantities of landfill leachate.

2. Materials and Methods

2. 3. Sample Collection

Leachate samples were obtained from the Environmental Complex for the final disposal of solid waste in the Santo Domingo canton, Ecuador. One gallon of landfill leachate was collected.

Cattle manure was sourced from the livestock farm at the Technical University of Machala. Two kilograms of cow manure were obtained as inoculum for the anaerobic digestion process.

Subsequently, the landfill leachate and cattle manure samples were stored under refrigeration at 4°C to ensure consistent experimental conditions for the co-digestion components.

2.4. Sample Preparation

In the laboratory setting, three hermetically sealed anaerobic reactors (R1, R2, R3) with a capacity of 500 mL were set up. Different volumes of substrates were mixed in each anaerobic reactor. Specifically, cattle manure and landfill leachate were added in a volumetric ratio of 75:25 (R1), 50:50 (R2), and 25:75 (R3), as shown in Table 1.

Table 1: Volumetric ratio of each treatment used in this research

Anaerobic Reactor	Landfill leachate (mL)	Cattle manure (mL)
R1	150	50
R2	100	100
R3	50	150

The total volume of the solution in each anaerobic bioreactor is 200 mL. The leachate collected from the landfill was pretreated with a 2 mm mesh to remove larger particles [14].

2.5. Measurement of Biogas Composition

The composition of methane (CH_4) and carbon dioxide (CO_2) was analyzed using a FULI 9790 II gas chromatograph. A syringe was used as the injection system for the generated biogas, which was stored in a 250 mL polypropylene bag. Hydrogen gas was used as the carrier gas, with a capillary column (30 m x 0.32 mm x 40 µm) and compressed air as the solvent. The gas chromatograph was equipped with a flame ionization detector (FID) [15].

3. Results and Discussion

The results obtained in Table 2 allow us to conclude that there is a positive effect of leachate on methane production in all three treatments when co-digested with cattle manure. It can be observed that the highest methane production (CH_4) occurred in R3, reaching values of 96.81% on day 36, while R1 had the lowest methane production with maximum values of 91.74% on day 16. These high methane values in all three treatments can be attributed to the synergistic effect of the mixture, where it is considered that aged leachate has a higher buffering capacity, as well as a more acclimated methanogenic consortium, leading to rapid methanogenesis of the organic load [11].

Table 2: Measurement of methane (CH_4) and carbon dioxide (CO_2) composition every 10 days.

	DAY 6		DAY 16		DAY 26		DAY 36		DAY 46	
	%CH_4	**%CO_2**	**%CH_4**	**%CO_2**	**%CH_4**	**%CO_2**	**%CH_4**	**%CO_2**	**%CH_4**	**%CO_2**
R1	65,25	2,11	91,74	7,15	91,23	6,99	90,49	3,05	91,07	4,99
R2	57,38	5,85	92,51	5,88	92,03	6,13	86,16	13,57	72,15	6,25
R3	69,87	24,81	89,08	10,54	93,78	6,12	96,81	3,07	96,66	2,91

The following Figure 1 shows the average methane production in R1, where it can be observed that from day 16 onwards, there are no significant differences at a 95% confidence level until day 46 of co-digestion using a 3:1 ratio of landfill leachate and cattle manure.

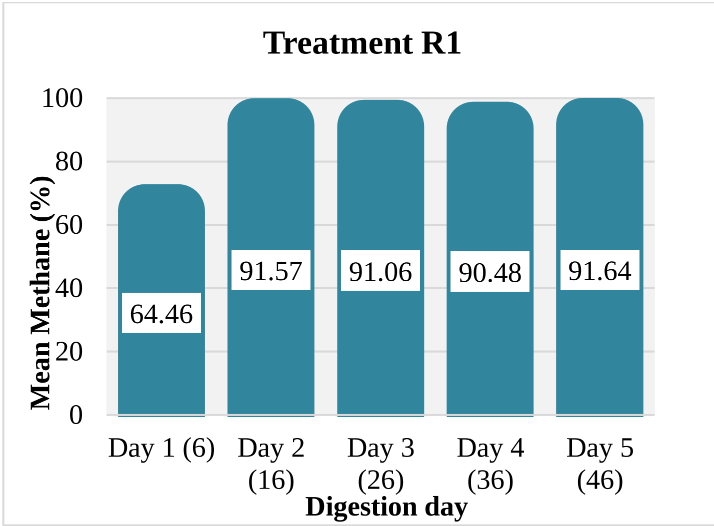

Fig. 1: Average methane production (%CH_4) per day of digestion in R1.

On the other hand, Figure 2 presents the methane production in R2, where a 1:1 ratio of landfill leachate and cattle manure was used. It can be observed that there are significant differences between day 6 of the digestion process with a methane average of 57.20% and the last day (day 46) which showed a decrease in methane percentage compared to the maximum values reached, with an average of 72.25%. However, the highest methane production achieved in this reactor occurred on days 16 and 26, which had values of 91.42% and 92.37%, respectively, where no statistically significant differences could be found between these two co-digestion periods at a 95% confidence level.

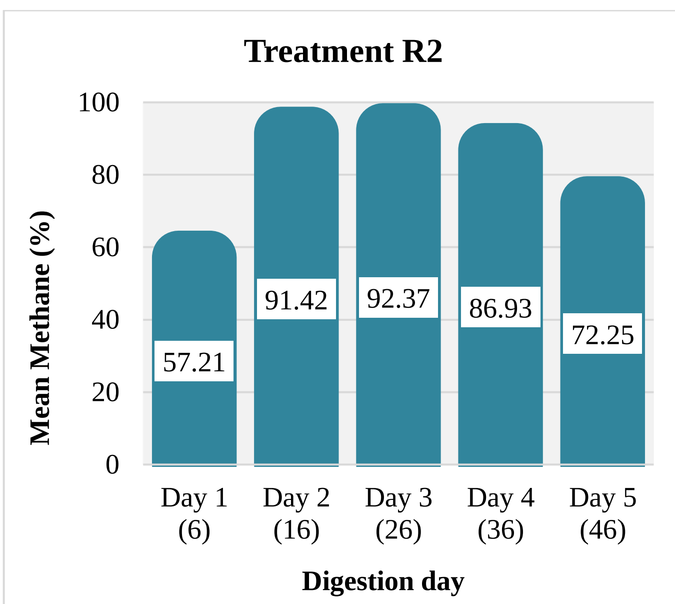

Fig. 2: Average methane production (%CH_4) per day of digestion in R2.

Additionally, Figure 3 demonstrates the methane production in R3, where a 0.3:1 ratio of landfill leachate and cattle manure was used. It can be observed that there are significant differences between day 6 of the digestion process with a methane average of 69.44% and day 16 which had a methane average of 89.45%. However, the highest methane production achieved in this reactor occurred on days 36 and 46, which had values of 96.23% and 96.43%, respectively, with no statistically significant differences found between these two co-digestion periods.

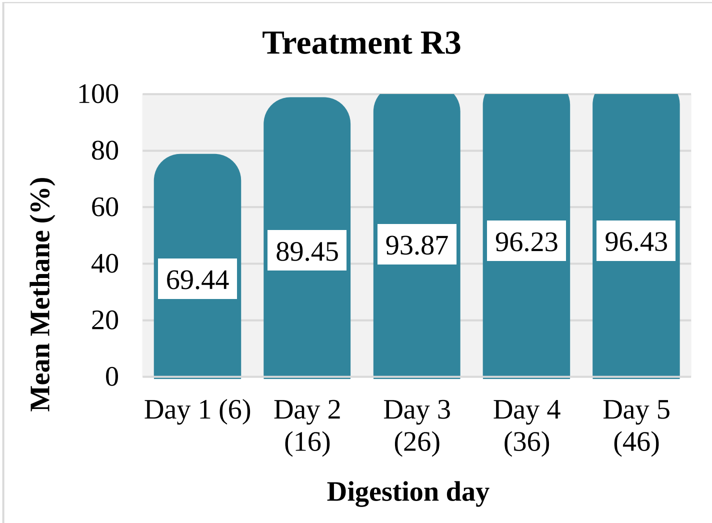

Fig. 3: Average methane production (% CH_4) per day of digestion in R3.

On the other hand, regarding the volume of biogas generated in treatment R1, Figure 4 shows that on day 6, it reached its highest volume production with a value of 198.33 mL of biogas, which is statistically significantly different from day 16 and day 36. Similarly, it can be concluded that the volume of biogas does not differ between day 26 and day 46, showing a decreasing trend in the mL of biogas over time. This can be explained by the presence of volatile fatty acids (VFAs) inhibiting the optimal production of biogas by methanogenic archaea in the reactor [11]. Factors such as rapid acidification, scarcity of bioavailable nutrients (especially nitrogen), and the presence of unsuitable materials, among others, contribute to this phenomenon [16].

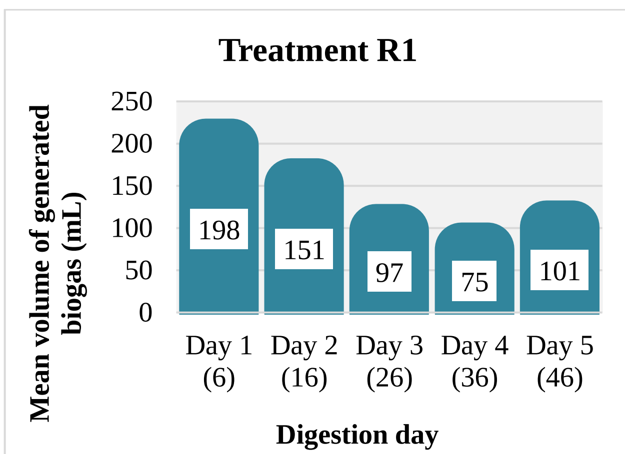

Fig. 4: Average biogas volume (mL) per day of digestion in R1.

Similarly, Figure 5 demonstrates that there were significant differences in the volume of biogas generated in treatment R2, with a consistent decrease in the amount of biogas produced over time during the anaerobic co-digestion process using a 1:1 ratio of landfill leachate and cattle manure.

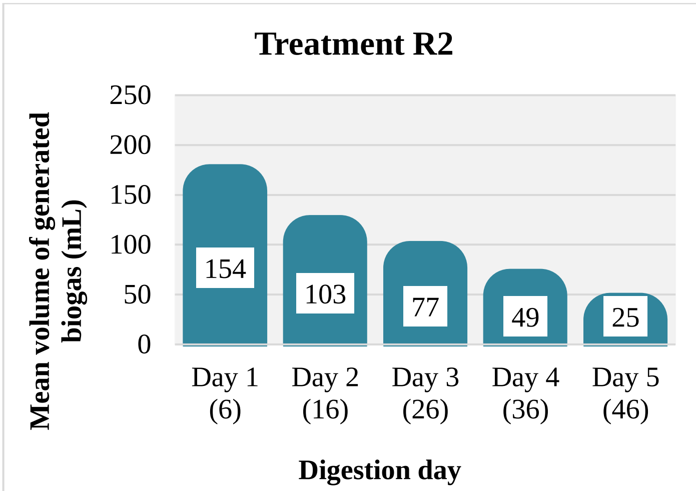

Fig. 5: Average biogas volume (mL) per day of digestion in R2.

Lastly, Figure 6 demonstrates that in the 0.3:1 ratio of landfill leachate and cattle manure, there are no significant differences in the volume of biogas generated between day 6 and day 36, with values of 101.67 mL and 99.33 mL, respectively. However, the trend of decreasing volume is confirmed compared to the last day of experimentation (day 46) in the digestion process, with an average generated volume of 48.33 mL.

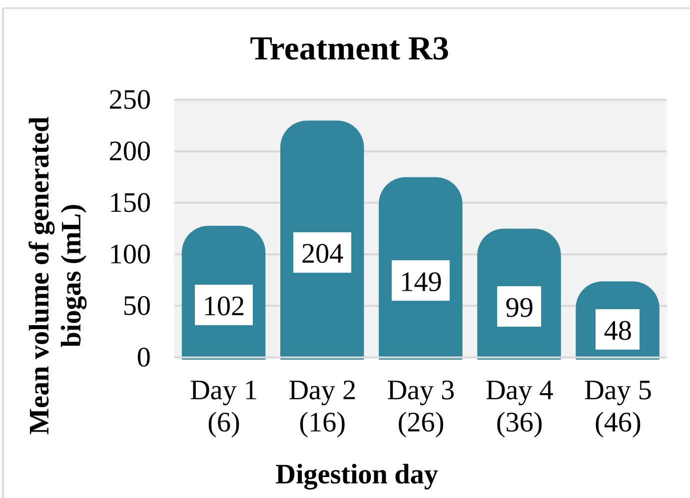

Fig. 6: Average biogas volume (mL) per day of digestion in R3.

It is important to mention that there is concordance between the volume of biogas generated in R3, with the maximum methane amount reached by the 0.3:1 ratio of landfill leachate and cattle manure used in this reactor, as mentioned in Table 2. Table 3 presents the Duncan test for the volume generated per day in reactor 3, confirming the maximum biogas volume obtained in this experimentation with a value of 203.67 mL reached on day 16 of anaerobic co-digestion, with a 95% level of reliability.

Table 3. Duncan test for the daily generated volume in reactor 3.

Reactor 3					
Duncan					
Digestion Day	N	Subset for alpha = 0.05			
		1	2	3	4
Day 5 (46)	3	48.33			
Day 4 (36)	3		99.33		
Day 1 (6)	3		101.67		
Day 3 (26)	3			149.00	
Day 2 (16)	3				203.67
Significance		1.000	.730	1.000	1.000

In this research, the maximum amount of methane generated in R3 after 36 days of co-digestion, measured by gas chromatography, consisted of a CH_4 percentage of 96.81±0.767% and CO_2 of 3.07±0.737%.

Our results are in line with another study [17], where the daily biogas production for the used reactors initially increased to a peak in the first 7 days and then gradually decreased. This can be explained by the rapid degradation of labile organic materials by microorganisms, leading to the first peak of methane production, while complex organic compounds decomposed slowly, resulting in carbon dioxide formation.

In this regard, other authors have stated that volatile fatty acids (VFAs) are intermediates in the methane formation pathway of anaerobic digestion and can be produced in similar biogas reactors to enhance the productivity of a digestion plant [18].

On the other hand, in R2 after 6 days of co-digestion, a lower CH_4 production was observed with 57.38±1.041% and a CO_2 content of 5.85±0.611% as determined by gas chromatography. One possible explanation for this is that the increase in solid concentration due to the percentage of added manure can affect mass transfer processes (substrate-cell) and reduce the efficiency of organic matter utilization by the present microbiota. Studies in this regard indicate that methanogenic activity decreases as the solid concentration in the reactor increases, due to the higher concentration of added cattle manure [19].

4. Conclusion

A positive effect of landfill leachate on methane production was determined through the three treatments when co-digested with cattle manure. It can be observed that the highest methane production (CH_4) occurred in R3, reaching values of 96.81% on day 36, while R1 had the lowest methane production with maximum values of 91.74% on day 16. These high methane values in all three treatments can be attributed to the synergistic effect of the mixture, where it is considered that aged leachates have a greater buffering capacity and a more acclimated methanogenic consortium, leading to rapid methanogenesis of the organic load.

Furthermore, there is agreement between the volume of biogas generated in R3 and the maximum amount of methane achieved through the 0.3:1 ratio of landfill leachate and cattle manure used in this reactor. Additionally, the Duncan test applied to the daily volume generated in reactor 3 confirms the maximum biogas volume obtained in this experimentation, with a value of 203.67 mL reached on day 16 of anaerobic co-digestion, with a 95% reliability.

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