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The efficiency of carbon dioxide production from aerobic digestion of refinery biological sludge

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ABSTRACT

Petroleum refineries produce significant biological sludge, and the CO_2 generated during its aerobic digestion is mostly unutilized. This study examined the efficiency of CO_2 production from refinery sludge under various biomass loading conditions. Sludge from the PETRONAS Chemical Olefins and Glycols wastewater treatment plant was collected to operate twelve bench-scale reactors for 10 days. A water displacement and CO_2 analyzer were used to measure CO_2 every 24 hours. Four reactors (R1, R4, R5, and R8) were considered analytically unreliable because three showed insufficient mixed liquor volatile suspended solids (MLVSS) reduction (ΔMLVSS < 100 mg/L), while R5 exhibited anomalous gas readings. However, MLVSS continuously declined in all reactors, confirming microbial activity. Specific CO_2 yields ranged from 605.98 mg CO_2/g MLVSS to 1,791.39 mg CO_2/g MLVSS throughout the eight reliable reactors. Reactor R10 (1,000 mL sludge; 50% volumetric fraction) provided the highest specific CO_2 yield among the tested conditions, obtaining approximately 91.9% of the theoretical maximum carbon conversion. These findings imply that there is an optimal sludge load at which microbial efficiency reaches its optimal sludge load at which microbial efficiency by overcrowding. This study provides the groundwork for improving aerobic digestion systems to enhance CO_2 extraction from refinery sludge on an industrial scale.

Keywords: carbon dioxide, aerobic digestion, refinery sludge, MLVSS, carbon capture, sludge loading, carbon mineralization, wastewater treatment.

INTRODUCTION

Rising atmospheric concentrations of carbon dioxide (CO_2) present a global concern that goes beyond the energy sector. Monthly averages as of May 2025 were 430.2 ppm, far greater than pre-industrial levels of 278 ppm in 1750. Despite international climate agreements, the gap is still growing. This development is influenced by industrial processes, such as wastewater treatment (WWT), in ways that are often underestimated (Global Energy Review 2025; Le Quéré et al., 2014). Petroleum refineries are extremely water-intensive industries, running continuous wastewater treatment systems. A key element of these systems is the activated sludge process, which uses aerobic microorganisms to break down organic pollutants into CO_2 and water. Sludge is a semi-solid wastewater treatment byproduct composed of water, organic matter, inorganic materials, and microbes. During the primary and secondary treatment phases, sludge is generated and then must undergo further processing to minimize its volume and environmental impact before being reused or disposed of (Friedlingstein et al., 2024; Nascimento et al., 2018; Werther & Ogada, 1998).

Aerobic sludge digesters are routinely used for sludge handling in facilities such as PETRONAS Chemical Olefin and PETRONAS Chemical Glycols (PCOGD), which operate a wastewater treatment plant (WWTP) generating a continuous

stream of biogenic CO_2 that is currently released to the atmosphere (Bishop, 1978). The CO_2 released is typically too diluted for conventional capture techniques, and aeration alone can account for 50%–80% of energy consumption in a treatment plant (Huang et al., 2023; Li et al., 2025; Yang et al., 2025).

This presents an important question: is it possible to use this biogenic CO_2 rather than releasing it? Unlike many other carbon sources, CO_2 is more accessible because it may be produced continuously in a monitored, instrumented, and controlled environment without the need for additional infrastructure (Gu et al., 2023; Li et al., 2025; Yang et al., 2025). However, a precise, quantitative understanding of CO_2 production rates and governing factors is necessary before any recovery or utilization plan can be designed. That basic need was addressed in this study. The biochemical process of aerobic sludge digestion is well known. Microorganisms oxidize organic materials under sustained aeration and switch to endogenous respiration, which catabolizes their own cell mass in the absence of external substrate (Tiwari et al., 2024; Waqas et al., 2023). The general reaction for microbial biomass oxidation can be stated as:

$$C_5H_7NO_2 + 5O_2 \rightarrow 5CO_2 + 2H_2O + NH_3 \quad (1)$$

One mole of microbial biomass can be completely oxidized to produce five moles of CO_2, or about 1.95 g CO_2/g biomass, based on Eq. 1(Tiwari et al., 2024). Due to variations in sludge compositions, aeration intensity, and reactor configuration, empirical studies have reported specific CO_2 production values ranging from 450–600 kg CO_2/ton dry solids in full-scale aerobic stabilizers to 1,000–1,400 mg CO_2/g VSS oxidized in bench-scale reactors (Environmental Protection Technology Series, 1975; Messenger et al., 2008; Sodiq et al., 2023). Refinery sludge has a distinct microbial community, a larger hydrocarbon content, and much higher levels of mixed liquor than municipal sludge. Refinery systems typically have mixed liquor suspended solids (MLSS) levels between 3,000 and 6,600 mg/L and mixed liquor volatile suspended solids (MLVSS) between 2,400 and 6,100 mg/L (Blatchford, 2017; Gasim et al., 2015; Razavi & Miri, 2015; Waheid & Al-Attabi, 2018). Biologically active, organically rich sludge is often indicated by an MLVSS/MLSS ratio of more than 70%. Moreover, refineries produce wastewater with BOD levels of 150-250 mg/L and COD levels of 300-600 mg/L (Rahi et al., 2021), placing extreme demand on dissolved oxygen (DO) levels within treatment systems. These characteristics imply that the dynamics of CO_2 production in refinery sludge may differ considerably from those found in municipal systems. Despite these variations, the production of CO_2 from aerobic digestion of refinery biological sludge has received limited experimental. The existing literature often discusses carbon capture methods or municipal sludge that require high-purity CO_2 streams, which are incompatible with aerobic digester conditions (Epa & Change Division, 1990; Ranieri et al., 2023). Importantly, no bench-scale quantitative assessments of the relationship between sludge loading and specific CO_2 output per unit of degraded biomass have been studied for refinery applications.

This study aimed to bridge this knowledge gap. Over a 10-day batch period, twelve bench-scale aerobic digestion reactors were operated with various sludge volumes. The goal was to find out how sludge loading impacts CO_2 production efficiency and to determine the optimal loading condition that maximizes specific yield under fixed aeration.

MATERIALS AND METHODS

Sludge collection and preparation

Biological sludge was taken from the aerobic digester unit of the PETRONAS Chemical Olefin and PETRONAS Chemical Glycols (PCOGD) refinery wastewater treatment plant Kerteh, Terengganu, Malaysia. To maintain microbial viability, samples were transported to laboratory under controlled temperature conditions. Before reactor preparations, the sludge was subsequently homogenized by manual stirring for 15 minutes after being screened through a fine mesh filter (mesh size:1 mm) to remove non-biodegradable debris. It is acknowledged that screening and manual mixing partially disrupt the native floc structure; however, these steps were necessary to ensure compositional uniformity across reactors and are consistent with standard bench-scale sludge preparation procedures Wastewater Engineering Treatment and Resource Recovery (2014)

Experimental framework

Twelve bench-scale aerobic digestion reactors were set up, each one of them had a 2 L working volume. Distilled water was added to each reactor to bring it to the same working volume, while the amount of raw sludge differs between them. From 100 mL in R1 to 1,200 mL in R12, the sludge volumes covered a wide range of biomass concentrations from dense to diluted. For 10 days, all reactors operated in batch mode with no additional feeding or sludge removal. Each of the twelve reactors represented a unique sludge-loading condition, and the experiment was conducted as a single run. Measurement replicates (triplicates) were applied for MLSS and MLVSS analysis (section 2.5). CO_2 concentration readings were recorded as a single measurement per reactor per 24-hour cycle (section 2.4), as each sampling bag was analyzed once using the portable CO_2 analyzer prior to replacement. As a result, standard deviations for CO_2-derived values cannot be calculated, and results are interpreted as exploratory. It is acknowledged that the absence of full experimental replication is a limitation, and future work should include replicated runs to strengthen statistical confidence. Sludge volumes ranged from 100 mL (R1) to 1,200 mL (R12) in increments of 100 mL per reactor

Reactor setup

Each reactor consisted of a sealed 2 L glass jar with two fine-bubble diffusers positioned at the bottom. Throughout the trial, each reactor was connected to an Atman HP-4000 aquarium air pump (Atman, China; 20W) that delivered a constant air flow of 35 L/min. Fine bubble diffusers were positioned above the sludge layer to ensure uniform aeration and high oxygen transfer efficiency throughout the sludge volume (Wastewater Engineering Treatment and Resource Recovery, 2014). All reactors were maintained at ambient laboratory temperature (approximately 25 ± 2°C) throughout the 10-day experimental period. Figure 1 shows the entire experimental setup, including the gas collection and displacement chamber system

Gas collection and CO_2 quantification

The gas produced during digestion was collected and measured using a water displacement method. A water-filled displacement chamber received the gases built up in each reactor's headspace through sealed tubing, and the displaced volume was recorded every 24 hours as a stand-in for the total amount of gas produced. After that, the gas stream was collected in 100 mL sampling bags, which were replaced daily to avoid backflow and contamination. Within 24 hours, CO_2 concentration in each sampling bag was recorded as a single measurement using a portable CO_2 analyzer (Quantek Instrument, Model Q21). The analyzer was factory-calibrated by the manufacturer prior to use. The record reading for each reactor was used directly for all subsequent calculations. The following equations were used to determine CO_2 volume, mass, and specific yield:

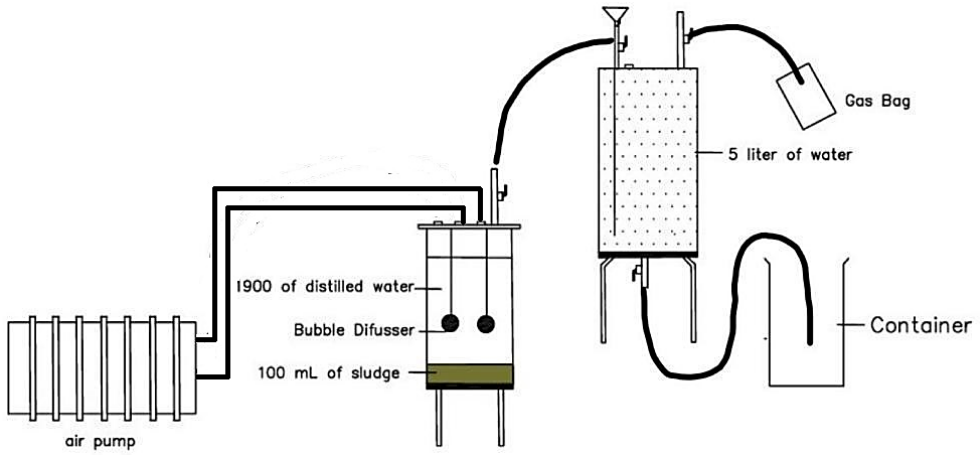

Figure 1. Schematic diagram of the bench-scale aerobic digestion reactor setup, showing the Atman HP-4000 air pump, digestion vessel (100 mL sludge, 1,900 mL distilled water), fine-bubble diffusers positioned above the sludge layer, water displacement gas collection system, and gas sampling

$$V_{CO_2,actual} = V_{displaced\ water} \times \frac{C_{CO_2}}{100} \quad (2)$$

where: $V_{CO_2,actual}$ is the actual CO_2 volume (L), Vdisplaced water is the total displaced water volume (L), and C_{CO_2} is the CO_2 concentration from the CO_2 analyzer (%).

$$n_{CO_2} = \times \frac{V_{CO_2\ actual}}{22.4} \quad (3)$$

$$m_{CO_2} = n_{CO_2} \times 44.1 \quad (4)$$

where: n_{CO_2} is the moles of CO_2 at STP (mol), and m_{CO_2} is the CO_2 mass using a molecular weight of 44.01 g/mol.

$$Y_{CO_2/X} = \frac{m_{CO_2}}{(\Delta MLVSS \times V_{liquid})} \quad (5)$$

where: $Y_{CO_2/X}$ is the biomass-normalized CO_2 yield (mg CO_2/g MLVSS), ΔMLVSS is the reduction in volatile solids (mg/L), and V_{liquid} is the reactor liquid volume (L).

Biomass characterization

MLVSS was measured on Day 0 and Day 10. From each reactor, a 10 mL sample was taken and diluted 1:100 with distilled water. Three duplicates of 30 mL aliquots from the diluted sample were filtered using Whatman glass fiber filter papers that had been previously weighed. MLSS were determined gravimetrically by drying at 105 °C for 1 hour, followed by ignition at 550 °C for 15 minutes. The weight loss between the two stages was divided by the filtered sample volume to determine MLVSS. Every process followed APHA Standard Methods (2017) (Parivallal et al., 2022). All calculations were based on the average of the three replicates.

When ΔMLVSS is very small, even modest measurement errors in CO_2 concentration or MLVSS become disproportionately high in the final yield values calculated by Eq. (5), rendering the result inaccurate. Reactors with a ΔMLVSS of less than 100 mg/L were therefore not included in the efficiency analysis. In the same way, yield comparisons excluded any reactor that produced a particular CO_2 yield above the theoretical maximum of approximately 1,950 mg CO_2/g biomass, which represents the upper limit set by complete microbial oxidation as illustrated in Eq. (1). For completeness, the findings include all reactors, even those that were excluded.

Statistical analysis

Descriptive statistics (mean and standard deviation) were calculated for all triplicate MLSS and MLVSS measurements. Due to the single-run experimental design (n=1 per loading condition), results are interpreted as exploratory. Spearman rank correlation analysis was conducted to assess the relationship between sludge volume and specific CO_2 yield among the eight valid reactors ($\rho = 0.095$, $p = 0.823$), and the results are discussed in section 3.5.

RESULTS AND DISCUSSION

MLVSS reduction during aerobic digestion

The MLVSS for each of the twelve reactors is shown in Table 1. The designed sludge volume gradient was reflected in the initial concentrations, which ranged from 700.000 mg/L in R3 to 3,166.667 mg/L in R12. All reactors showed a reduction in MLVSS by Day 10 (Table 1), confirming active aerobic oxidation over the whole experiment. MLVSS decreased considerably among reactors, ranging from 38.889 mg/L in R1 to 322.222 mg/L in R12. Higher sludge volumes were generally associated with greater degradation, which is consistent with more substrates being available. However, this trend was not entirely linear; for example, R3 (300 mL) showed greater MLVSS degradation than R4 (400 mL). This suggests that the degradation results were also influenced by variables other than the initial loading volume, such as aeration distribution and initial sludge composition.

Based on the ΔMLVSS reduction below 100 mg/L, reactors R1 (38.889 mg/L), R4 (77.778 mg/L), and R8 (94.444 mg/L) were excluded from the specific yield analysis. Reactor R5 was additionally excluded due to anomalous gas concentration readings. Thus, eight reactors (R2, R3, R6, R7, R9, R10, R11, R12) were retained for efficiency comparison.

Effect of sludge loading on biomass reduction

The effect of sludge loading on ΔMLVSS throughout the 10-day digestion period is evaluated in Figure 2. ΔMLVSS generally rises with sludge volume, from 38.889 mg/L (R1) to

Table 1. Initial and final MLSS and MLVSS concentrations (Mean ± SD from three gravimetric replicates) and corresponding ΔMLSS and ΔMLVSS for all twelve aerobic digestion reactors after a 10-day digestion period.

Reactor	Sludge vol. (mL)	Initial MLSS (mg/L)	Final MLSS (mg/L)	ΔMLSS (mg/L)	Initial MLVSS (mg/L)	Final MLVSS (mg/L)	ΔMLVSS (mg/L)
R1⁺	100	1600.00 ± 0.00	1300.00 ± 133.33	300.00	1016.67 ± 16.67	977.78 ± 171.06	38.89
R2	200	1683.33 ± 116.67	1500.00 ± 66.67	183.33	1100.00 ± 66.67	1000.00 ± 88.19	100.00
R3	300	1811.11 ± 19.24	711.11 ± 167.78	1100.00	700.00 ± 152.75	477.78 ± 107.15	222.22
R4⁺	400	1733.33 ± 133.34	1688.89 ± 69.39	44.44	1200.00 ± 66.67	1122.22 ± 117.06	77.78
R5*	500	—	—	—	—	—	—
R6	600	2566.67 ± 208.17	2411.11 ± 183.58	155.56	2200.00 ± 88.19	1988.89 ± 50.92	211.11
R7	700	2611.11 ± 195.31	2544.44 ± 101.84	66.67	2322.22 ± 153.96	2088.89 ± 214.30	233.33
R8⁺	800	2411.11 ± 50.92	2311.11 ± 164.43	100.00	2094.44 ± 67.35	2000.00 ± 200.00	94.44
R9	900	2711.11 ± 107.15	2611.11 ± 203.67	100.00	2400.00 ± 100.00	2255.56 ± 234.13	144.44
R10	1000	2800.00 ± 145.30	2733.33 ± 120.18	66.67	2500.00 ± 145.30	2333.33 ± 66.67	166.67
R11	1100	3455.56 ± 50.92	3311.11 ± 333.89	144.44	2911.11 ± 83.89	2777.78 ± 384.90	133.33
R12	1200	3755.56 ± 101.84	3611.11 ± 126.20	144.44	3166.67 ± 100.00	2844.44 ± 619.44	322.22

Note: ⁺Reactors R1, R4, and R8 were excluded from specific yield analysis due to insufficient MLVSS reduction (ΔMLVSS < 100 mg/L), which renders yield calculations mathematically unreliable. *R5 excluded due to anomalous gas concentration readings.

322.222 mg/L (R12), suggesting higher microbial degradation potential under larger organic loading. In mid-range reactors, there are clear deviations from the linear relationship. For example, R3 has a greater ΔMLVSS (222.222 mg/L) than R4 (77.778 mg/L), suggesting that degrading efficiency is not only controlled by sludge volume. Rather, performance was likely influenced by operational variability, including localized differences in sludge distribution, oxygen transfer efficiency across different biomass concentrations, and the inherent heterogeneity of biological sludge composition. While all reactors were prepared under identical aeration conditions and

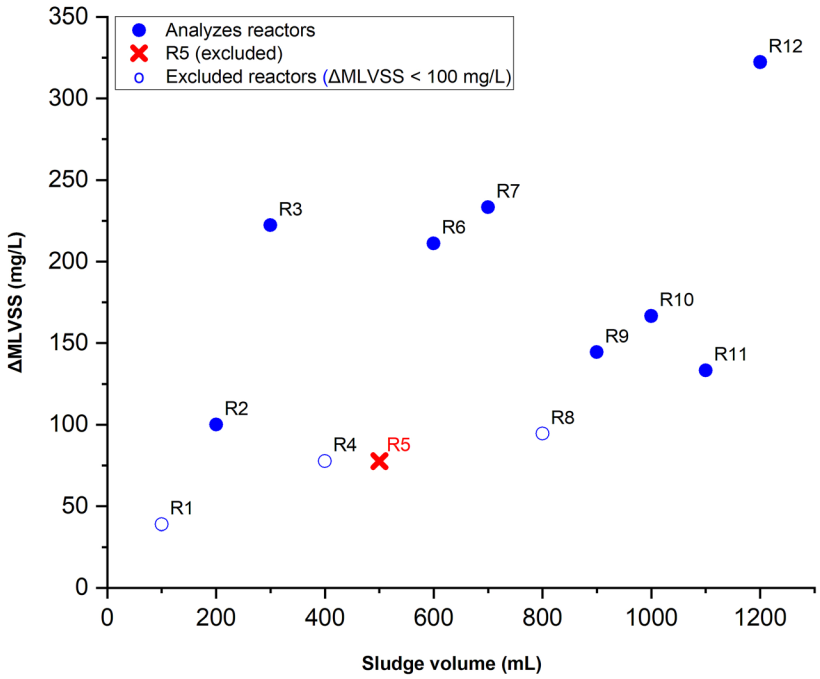

Figure 2. Relationship between sludge loading volume and MLVSS reduction (ΔMLVSS) over the 10-day aerobic digestion period. Blue circles = analyzed reactors; hollow circles (R1, R4, R8): excluded from efficiency analysis (ΔMLVSS < 100 mg/L); Red x = R5: excluded due to anomalous readings. All reactors are shown for completeness.

exposed to the same ambient laboratory temperature, these micro-scale variabilities could not be eliminated, and this should be considered when interpreting inter-reactor comparison. Overall, ΔMLVSS values are more consistent and increased during intermediate-to-high loading conditions, suggesting the best balance between aeration capacity and substrate availability.

Biomass stability and organic fraction (final MLVSS/MLSS ratio)

After 10 days of aerobic digestion, the MLVSS/MLSS ratios ranged from 66% to 87%, as illustrated in Table 2, indicating that most of the remaining solids were still organic and biologically active. The highest ratios (82–87%) were achieved by R6 to R10, indicating a greater proportion of the remaining solids were organic and potentially biologically active, which is consistent with more effective aerobic oxidation in these reactors. R10, with a sludge volume of 1000 mL, had the best balance between aeration and biomass concentration, as recorded by its ratio of 85%. Because of this condition, microorganisms maintained their high level of activity, which results in effective stabilization and steady CO_2 production. The ratios were noticeably lower (66%-75%) in reactors with smaller sludge volumes, such as R1 to R4. This implies that even though there was oxygen, biological oxidation was reduced because the microbial mass was too low or the supply of substrate was limited. The MLVSS/MLSS ratios and CO_2 yields reported here therefore not only biological activity, but also physicochemical changes introduced during sample preparation. This is a recognized limitation of the study and should be considered when interpreting the efficiency results. On the contrary, the reactor with the greatest sludge volume, R12, displayed a slight decrease in ratio (79%), most likely due to restricted oxygen transfer in denser sludge, which aligns with the well-documented drop in oxygen transfer efficiency as biomass concentration increases. Although oxygen transfer rates were not measured directly in this study, the trend observed here is consistent with findings reported in the literature regarding high biomass conditions (Wastewater Engineering Treatment and Resource Recovery, 2014)

Overall, these results clearly demonstrate that the MLVSS/MLSS ratio was directly affected by the volume of sludge in each reactor. While reactors with either too little or too much sludge demonstrated lower microbial efficiency, those with moderate sludge volumes achieved better biological balance and more effective degradation of organic matter. Hence, it seems that the favorable conditions for aerobic digestion are maintained at an intermediate sludge volume, especially around

Table 2. Final MLVSS/MLSS ratio after 10 days of aerobic digestion with qualitative interpretations. Interpretations are based on MLVSS/MLSS ratios only; no direct microbial characterization was conducted

Reactor	Final MLVSS/MLSS	Short Interpretation
R1⁺	75%	Moderate organic content; stable microbial activity
R2	67%	Reduced organic fraction; possible biomass decay
R3	67%	Low organic content; uneven aeration or sludge settling
R4⁺	66%	Lower biodegradation efficiency
R5*	–	Excluded from analysis
R6	82%	Strong microbial stability and active oxidation
R7	82%	High organic fraction; efficient aeration
R8⁺	87%	Highest ratio; excellent biological performance
R9	86%	High biological stability; sustained activity
R10	85%	Most favorable loading condition
R11	84%	High solids load; good but slightly oxygen-limited activity
R12	79%	Slight drop due to limited oxygen transfer in dense sludge

Note: ⁺Reactors R1, R4, and R8 were excluded from specific yield analysis due to insufficient MLVSS reduction (ΔMLVSS < 100 mg/L), which renders yield calculations mathematically unreliable. *R5 excluded due to anomalous gas concentration readings. SD for CO_2 concentration and yield values cannot be calculated as each loading condition was operated as a single reactor run (n = 1). This is acknowledged as a limitation; future work should incorporate fully replicated experimental runs.

1000 mL, as demonstrated in R10, supporting both efficient stabilization and enhanced CO_2 production.

Interpretations are based on MLVSS/MLSS ratios and are indicative only. No direct microbial characterization, such as microscopy or sequencing, was carried out. Conclusions about biological activity are drawn from solids fractionation data and should be read with caution, given the pretreatment steps applied to the sludge in the study.

Total CO_2 production

The total CO_2 mass reported here represents the cumulative sum of daily CO_2 production measured over the full 10-day digestion period, calculated by summing the daily CO_2 mass values derived from Equations 2–4 for each 24-hour interval. The eleven reactors (excluding R5) showed a range from 134.808 mg (R8) to 601.471 mg (R12), as illustrated in Table 3. Remarkably, R10 generated 597.129 mg of CO_2 with 1,000 mL of sludge, which was nearly identical to R12's 1,200 mL. This finding suggests that R10 produced a similar amount of CO_2 overall with 20% smaller volume of sludge, indicating a more effective process at that specific loading. As a volumetric proxy for gas generation, total displaced water generally increased with sludge volume, from 11.5 L in R6 to 224.1 L in R12. However, the total CO_2 mass did not follow a consistent pattern across reactors, as shown in Figure 3. At higher loadings this relationship reached a plateau. While containing 20% more sludge than R10, R12 only displaced 2.6 L more. According to earlier aeration studies, this observed flatness is consistent with oxygen diffusion becoming a limiting factor in denser sludge.

Specific CO_2 yield per unit biomass

The specific CO_2 yield per gram of initial MLVSS varied significantly between the reactors, as shown in Figure 4, indicating the impact of sludge concentration and oxygen transfer on microbial oxidation efficiency. The CO_2 yield varied from 605.98 mg CO_2/g MLVSS in R6 to 1,791.39 mg CO_2/g MLVSS in R10. While the lowest production was recorded in R3 (722.25 mg CO_2/g MLVSS) and R8 (713.69 mg CO_2/g MLVSS). This pattern suggests that the availability of oxygen relative to microbial mass, rather than the amount of sludge, controlled the production of CO_2. Higher CO_2 yield per unit of volatile solids was exhibited in reactors with moderate sludge loadings, especially R9, R10, and R12, suggesting that these systems maintained more favorable aerobic conditions. On the other hand, reactors with extremely low sludge concentration (R1 and R2) or very high concentration (R11 and R12) showed lower specific

Table 3. CO_2 production results across all twelve aerobic digestion reactors. [+] and * reactors shown for completeness only and excluded from specific yield comparisons

Reactor	Sludge vol. (mL)	CO_2 conc. (%)	Disp. water (L)	Actual vol. (L)	Mass CO_2 (mg)	Yield (mg/g MLVSS)
R1[+]	100	1.084	15.8	0.1713	336.417	4,325.360
R2	200	1.336	17.5	0.2339	459.227	2,296.135
R3	300	1.062	15.4	0.1635	321.002	722.253
R4[+]	400	0.496	19.2	0.0953	187.032	1,202.350
R5 *	500	2.485	15.8	0.3927	771.048	4,956.739
R6	600	1.133	11.5	0.1303	255.859	605.982
R7	700	0.787	20.5	0.1613	316.695	678.632
R8[+]	800	0.554	12.4	0.0687	134.808	713.688
R9	900	1.009	19.6	0.1977	388.162	1,343.638
R10	1,000	1.414	21.5	0.3041	597.129	1,791.387
R11	1,100	0.828	22.8	0.1888	370.674	1,390.029
R12	1,200	1.271	24.1	0.3063	601.471	933.317

Note: [+]Reactors R1, R4, and R8 were excluded from specific yield analysis due to insufficient MLVSS reduction (ΔMLVSS < 100 mg/L), which renders yield calculations mathematically unreliable. *R5 excluded due to anomalous gas concentration readings. SD for CO_2 concentration and yield values cannot be calculated as each loading condition was operated as a single reactor run (n = 1). This is acknowledged as a limitation; future work should incorporate fully replicated experimental runs.

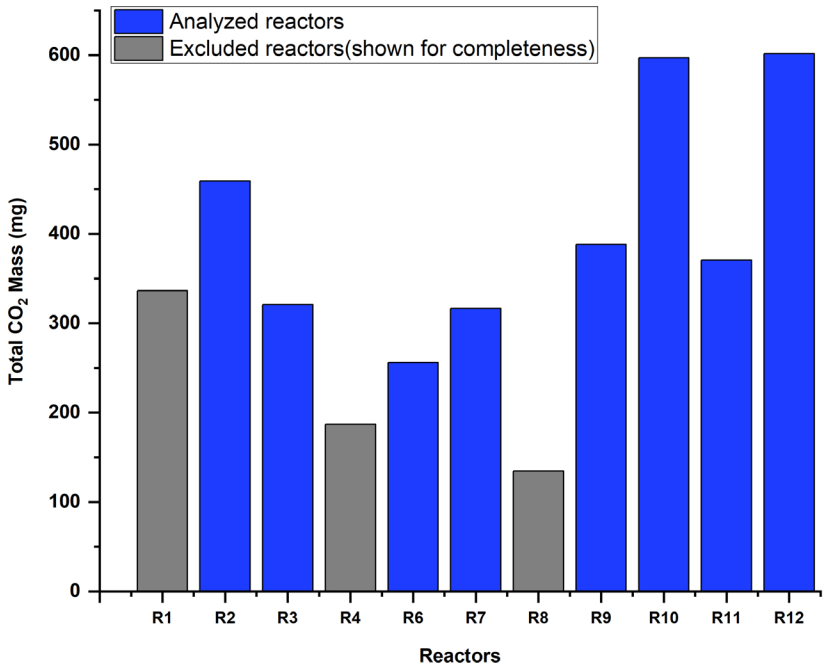

Figure 3. Total CO_2 mass produced per reactor over the 10-day aerobic digestion period (R5 excluded). Grey bars (R1, R4, R8) are shown for completeness but were excluded from efficiency analysis (ΔMLVSS < 100 mg/L). SD is not reported for CO_2 values as each loading condition was a single reactor run (n = 1)

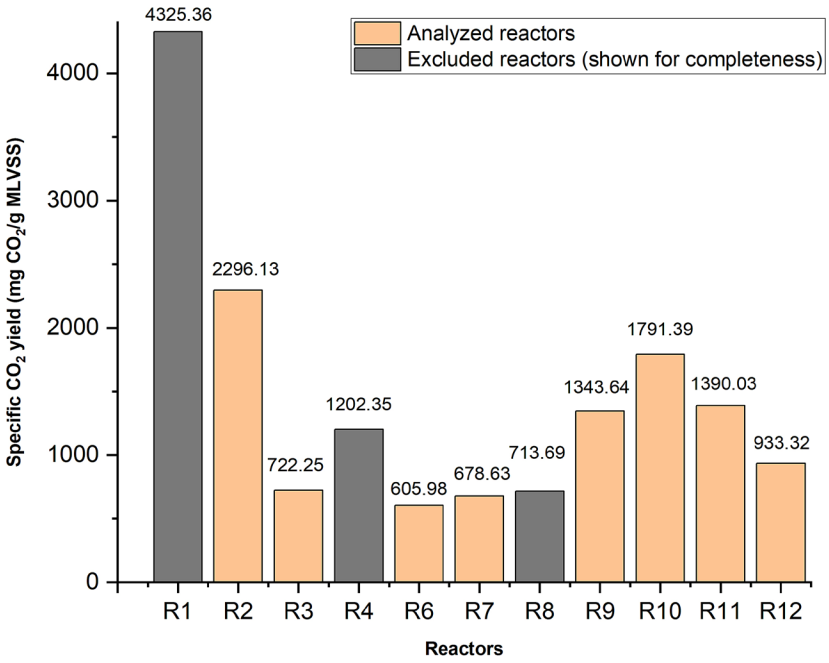

Figure 4. Specific CO_2 yield per gram of initial volatile solids (MLVSS) for each reactor. Grey bars (R1, R4, R8) are shown for completeness but excluded from efficiency comparisons. R5 excluded due to anomalous gas readings excluded). SD is not reported for CO_2 values as each loading condition was a single reactor run (n = 1)

CO_2 yields. This is probably because of limited oxygen transfer efficiency or localized microbial inhibition. Spearman rank correlation analysis among the eight reactors showed no meaningful relationship between sludge volume and specific CO_2 yield. This supports the view that oxygen transfer efficiency, rather than the amount of biomass, drives CO_2 production efficiency per unit MLVSS. Collectively, these results suggest that maximizing carbon oxidation during aerobic digestion requires a balanced ratio of biomass to aeration capacity.

Sludge loading drives efficiency

The results show that sludge loading and CO_2 production efficiency interact critically. The initial sludge volume was not the only factor influencing the specific CO_2 yield per unit biomass. Because there was less biomass available for degradation at low sludge volumes (R1-R4), even moderate CO_2 production generated large apparent yields. However, the yield calculations were compromised by very low ΔMLVSS values and the limited absolute amount of CO_2 captured. On the other hand, even with plenty of substrate, the aeration system appeared to have trouble supplying the oxygen required at a high sludge volume (R11, R12). This limitation reduced the specific yield by impeding the effective oxidation of biomass. Reactor R10 demonstrated the most favorable balance between these two constraints among the tested loading conditions. The biomass concentration was high enough to produce a significant CO_2 output, and the aeration capacity was sufficient to maintain active endogenous respiration throughout the 10-day period. This interpretation is consistent with aerobic digestion studies showing declining solid removal at high sludge concentration [9, 20] and findings that identified gas-liquid mass transfer efficiency as a common limiting factor in biological CO_2 systems. The practical implication is obvious: adding more sludge than the aeration system can handle does not enhance CO_2 capture; rather, it just processes a larger volume of sludge at a lower efficiency. Therefore, rather than considering these factors separately, any scale-up of this approach requires a precise matching of aeration capacity to sludge loading. The Spearman correlation result confirms that no simple relationship exists between sludge volume and specific CO_2 yield, which further supports the aeration-driven efficiency pattern seen throughout this study.

CONCLUSIONS

The study results demonstrate that CO_2 production from aerobic digestion of biological sludge does not just increase with sludge volume. Rather, it depends on how well the aeration system can meet the oxygen demand of the microbial mass. Eight reactors (R2, R3, R6, R7, R9, R10, R11, R12) remained for comparison after excluding four reactors: R1, R4, and R8 (ΔMLVSS < 100 mg/L, rendering yield calculations mathematically unreliable) and R5 (anomalous Gas concentration readings). The 1,000 mL sludge loading achieved the highest value at 91.9% of the theoretical maximum, with specific CO_2 yields ranging from 605.98 to 1,791.39 mg CO_2/g MLVSS. Beyond this point, adding more sludge did not improve yields, suggesting that oxygen transfer is the limiting factor at higher concentrations. When combined, these findings demonstrate that the best conditions for CO_2 recovery from refinery aerobic digesters are an intermediate loading condition and that matching aeration capacity to sludge loading is more important than merely increasing sludge volume.

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