



Full-Scale Anaerobic Co-Digestion of Sewage Sludge and Organic Wastes: Influence of Organic Loading Rate (OLR) and Substrate Composition on Process Indicators.

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Highlights

- Co-digestion of sewage sludge, fish waste and fruit and vegetable waste was evaluated in real scale.
- The OLR range of 2 to 3.5 Kg_{VS}/m³_{REACTOR}.day is linked to the best production results.
- Best results were achieved with a mixture ratio of 7:1:2 (SS: FVW: FW).

Introduction

Anaerobic digestion (AD) is a waste treatment technology based on the metabolization of organic matter by bacteria and archaea under an anoxic environment. The outcome of this process is the generation of biogas, rich in methane, which can be used to generate thermal energy, electricity, and biofuels (Mignogna et al., 2023).

In Brazil, sewage sludge (SS) has an estimated biogas production potential of 493 million Nm³ per year (ABIÓGÁS, 2021). However, only 9% of domestic treatment plants utilize this substrate, mainly due to its low organic loading (CIBiógás, 2024; Grosser, 2017). In this context, the co-digestion of SS with complementary organic substrates has emerged as a strategy to enhance AD efficiency (Grosser, 2017). Fish waste (FW) and fruit and vegetable waste (FVW) are notable co-substrates employed in co-digestion with SS due to their high volatile solids content, biodegradability, and, in the case of FW, lipid content – factors that enhance biogas generation (Chairattanawat et al., 2022; Di Maria et al., 2014). Nevertheless, in full-scale plants implementing this type of co-digestion, controlling parameters such as organic loading rate (OLR) and substrate mixture ratio is essential to avoid acidification and efficiency loss (Charles et al., 2011; Hagos et al., 2017). In this sense, the performance and stability of AD can be assessed through indicators such as biogas productivity (Nm³_{BIOGÁS}/m³_{REACTOR}.day) and methane concentration (%), which are sensitive to operational changes and reflective of the digestion efficiency (Bensmann et al., 2016). Additionally, the FOS/TAC ratio – representing the proportion between volatile fatty acids (VFA) concentration and system alkalinity – serves as a key stability monitoring parameter (Nkuna et al., 2021). In this sense, values of FOS/TAC ratio above 0.4 indicate a tendency towards acidification, while values below 0.3 suggest system underfeeding (Lili et al., 2011).

Accordingly, the objective of this study is to evaluate the impact of variations in OLR and substrate mixture ratios on biogas productivity, methane concentration, and the FOS/TAC ratio in a biogas full-scale plant. The aim is to establish recommended operational ranges that maximize the productive efficiency of the plant and provide guidance for the operation of other sewage sludge co-digestion plants.

Material and Methods

The study was conducted at a biogas plant located in the Metropolitan Region of Curitiba (Paraná, Brazil), where the process is based on the anaerobic co-digestion of SS, FVW and FW. The system comprises two hydrolysis tanks (600 m³ each), two 5,000 m³ CSTRs, and a 3,400 m³ post-digester, all operating in parallel under mesophilic conditions. The biogas produced is treated and converted into electrical energy.

The independent variables adopted were the average OLR applied to CSTRs (Kg_{VS}/m³_{REACTOR}.day) and the substrate mixture ratio based on volatile solids (kg_{VS}_{SUBSTRATE}/day). Statistical analysis was performed using simple and polynomial linear regression models to identify relationships between these variables and the following dependent parameters: average FOS/TAC ratio of CSTRs (Lili et al., 2011), biogas productivity (BP, Nm³_{BIOGÁS}/m³_{REACTOR}.day), and methane concentration (MC, %). For the calculation of BP, biogas flow was



continuously measured using a vortex flow meter and logged daily. Meanwhile, MC was determined from the daily average of eight biogas quality measurements taken in the biogas supply line to the generators, using a portable analyzer. Mean BP and MC values were used to evaluate the impact of OLR ranges and substrate mixture ratios on process performance. Descriptive statistics and box plot graphics were used for clear parameterization and data interpretation. Results were compared with BMP assay outcomes per VDI 4630 (2016), performed by an external laboratory. The data presented cover the period from January 2024 to April 2025, with a confidence level of 95%.

Results and Discussion

Table 1 shows that SS is the substrate contributing the highest input of volatile solids (VS) due to its larger reception volume compared to the other substrates, enhancing system buffering capacity via near-neutral pH (Hagos et al., 2017). In contrast, FVW and FW contribute to the viability of the co-digestion process due to their higher biogas production potential. Nevertheless, their more acidic characteristics require constant monitoring of volatile fatty acid (VFA) concentrations in the digesters in order to prevent inhibitory acidification (Chairattanawat et al., 2022). In this regard, FVW's frequent supply ensures continuous high VS input, whereas FW, though less frequent, significantly influences biogas production and quality due to its elevated lipid, total solids, and VS contents, corroborated by BMP assays conducted (Chairattanawat et al., 2022).

Table 1: Summary of the Characteristics of Received Substrates and Confidence Level of the Impact on OLR

Substrate	TS (%)	VS (%TS)	pH	INPUT FLOW RATE (m ³ _{SUBSTRATE} /day)	DAILY VS INPUT PER SUBSTRATE (Kg _{VS} /day)	BBP (L _{BIOGAS} /Kg _{VS})	CH ₄ (%)
Sewage Sludge	2.9±0.5	72.1±8.6	6,46	300±82	17,146±4,641	459	65
Fruit and Vegetable Waste	9.0±1.9	88.6±6.2	4,11	39±17	3,083±1,631	899	55
Fish waste	26.1±8.3	89.3±10.5	5,10	28±6	6,474±2,255	1060	67

Figure 1 shows that the average OLR applied to the digesters during the analyzed period was $2.23 \pm 0.68 \text{ Kg}_{\text{VS}}/\text{m}^3_{\text{REACTOR}} \cdot \text{day}$, being strongly influenced by both the volume of sewage sludge (SS) received and the frequency and magnitude of FVW and, especially, FW incorporation. Accordingly, the highest OLR values occurred during the simultaneous co-digestion of all three substrates. It is noteworthy that these values are consistent with previous studies involving the co-digestion of SS with food waste, indicating that the process carried out in the plant is stable and efficient. Zhang et al. (2022) reported higher conversion efficiency of volatile solids into methane at OLRs up to $3.5 \text{ Kg}_{\text{VS}}/\text{m}^3_{\text{REACTOR}} \cdot \text{day}$, while Gou et al. (2014) highlighted that OLRs up to $5.0 \text{ kg}_{\text{VS}}/\text{m}^3 \cdot \text{day}$ can ensure adequate stability in an AD under mesophilic conditions.

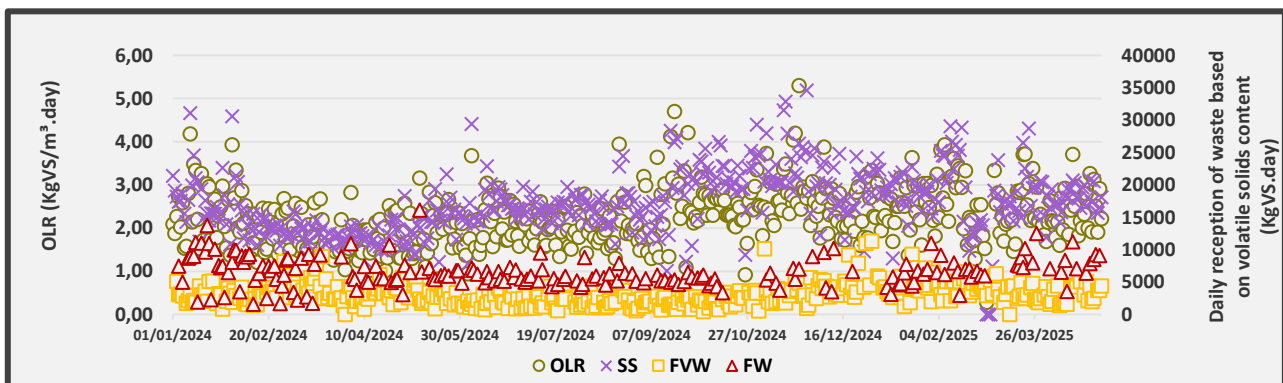


Figure 1 Impact of substrate reception based on their volatile solids (VS) on the OLR.



During the analyzed period, the anaerobic digestion system exhibited an average BP of $0.94 \pm 0.22 \text{ Nm}^3_{\text{BIOGAS}}/\text{m}^3_{\text{REACTOR}}\cdot\text{day}$ and an average MC of $62.77 \pm 2.15\%$. As shown in Figure 2, the best results were observed under intermediate OLRs, as reflected by the moderately strong correlations identified through polynomial regression (Duong et al., 2023). In terms of biogas productivity, the OLR range of 2 to $3.5 \text{ kgVS}/\text{m}^3\cdot\text{day}$ maintained efficiency levels comparable to the plant average, with the range of 3 to $3.5 \text{ kgVS}/\text{m}^3\cdot\text{day}$ yielding the highest biogas productivity. On the other hand, the range of 2 to $2.5 \text{ kgVS}/\text{m}^3\cdot\text{day}$ was associated with the highest methane concentrations in the biogas.

OLRs outside the optimal ranges—either too low or too high—negatively impacted process performance. According to Nkuna et al. (2021), low OLRs can lead to biomass deficiency and reduced microbial activity, whereas high OLRs tend to cause volatile fatty acid (VFA) accumulation, surpassing the metabolic capacity of methanogenic microbial and favoring acidification of the medium (Charles et al., 2011). This scenario regarding the impact of OLR on VFA accumulation is further supported by Figure 2, which shows a direct correlation between increasing OLR and FOS/TAC values. Nevertheless, throughout the study, this ratio remained within the optimal range of 0.3 to 0.4 in the CSTRs effluent, which is considered ideal for biogas production (Lili et al., 2011).

The proportion of substrates composing the organic loading rate showed a strong correlation with the process performance indicators. The best outcomes were observed when fish waste (FW) was included in the substrate mix, corroborating the biochemical methane potential (BMP) assay results. Accordingly, the most efficient co-digestion configuration was achieved with a 7:1:2 mixture ratio (SS:FVW:FW), based on volatile solids (VS) input, highlighting the synergistic effect between the buffering capacity of sewage sludge (SS) and the high biogas and biomethane potential of FVW and, primarily, FW. Conversely, excessive reception of FVW—especially when associated with low SS input and absence of FW—significantly compromised process efficiency. This trend was consistent with both BMP test results and findings by Di Maria et al (2014), who attributed the decline in methane content and biogas production to imbalances caused by high proportions of FVW in co-digestion with SS, which may lead to excessive accumulation of VFAs in the reactors.

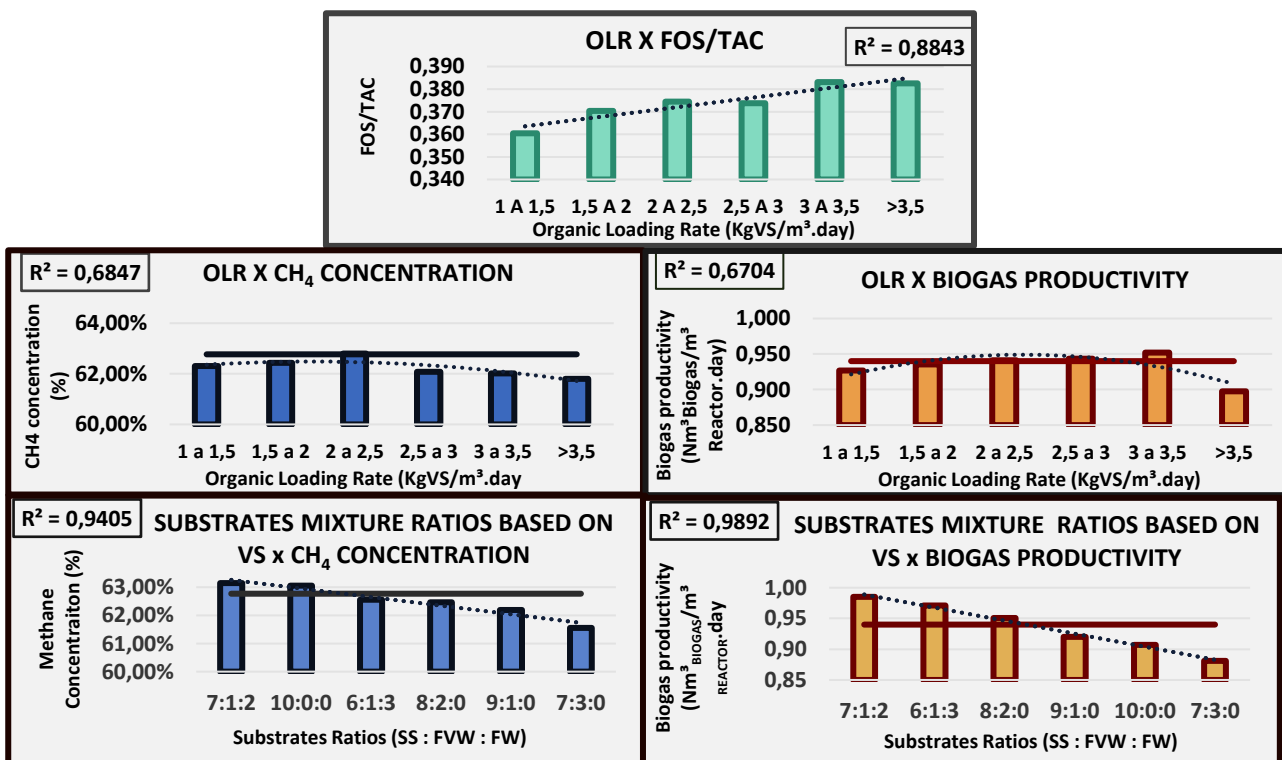


Figure 2 Correlation between OLR and substrate proportion with process indicators.



Conclusion

The co-digestion process of sewage sludge (SS), fruit and vegetable waste (FVW), and fish waste (FW) proved effective for producing biogas with a high methane content, due to the complementary physicochemical characteristics of these substrates. Variations in the substrates mixture ratios based on volatile solids (VS) content directly influenced the organic loading rate (OLR) applied to the reactors and the process performance indicators. The 7:1:2 (SS: FVW: FW) mixture ratio yielded the highest biogas productivity and methane concentration, combining the buffering capacity provided by SS with the high energy potential of FW and FVW.

Furthermore, OLR was confirmed as a critical operational parameter, with intermediate values between 2 and 3.5 kg_{VS}/m³·day being associated with higher efficiency and system stability. Operating within this range helps to prevent both overloading and underfeeding—conditions that impair methanogenic microbial activity. These findings underscore the importance of full-scale studies to provide technical support for the advancement of the biogas market in the sanitation sector across Latin America, showing that proper control of both the substrate mixture ratio and the OLR applied to digesters can improve performance in full-scale operations.

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