



## ANAEROBIC DIGESTION OF RAW EFFLUENT AND FLOAT SLUDGE FROM POULTRY SLAUGHTERHOUSE: EVALUATION OF THE W/M RATIO AND THE INFLUENCE OF FLOAT SLUDGE CONTENT ON BIOGAS PRODUCTION

Thays Majara Silva Araujo<sup>1</sup>, Simone Damasceno Gomes<sup>2</sup>, Divair Christ<sup>3</sup>, Kátia Cristina Fagnani<sup>4</sup>, Tatiane Martins de Assis<sup>5</sup>, Tamiris Uana Tonello<sup>6</sup>, Aruane Leticia da Silva Tomoto<sup>7</sup>, Rodrigo Sequinel<sup>8</sup> and Guilherme Fagnani de Souza<sup>9</sup>

### ABSTRACT

Poultry slaughterhouses generate large volumes of effluents with a high content of organic matter and lipids. Among the alternatives available for treatment, anaerobic digestion provides the transformation of these effluents into biogas. The objective of this work was to evaluate the anaerobic codigestion of fresh sludge from the flotator to the raw effluent of a poultry slaughterhouse. The codigestion assays were carried out in reactors (500 mL of total volume and 300 mL of useful volume), operated in batch under mesophilic conditions ( $30 \pm 1$  °C), with an incubation time of 108 days. An experimental design of the Central Rotational Composite Design (RCD) was adopted, comprised of a  $2^2$  factorial with four trials at levels +1 and -1, four trials at the levels of axial points (-1.414 and +1.414) and one more triplicate at the central point (0), the response variables were: accumulated production of CH<sub>4</sub> (L) and yield CH<sub>4</sub> (L CH<sub>4</sub>/g SV added), five levels of fresh sludge addition from the flotator (V/V) (15.9, 20, 30, 40 and 43.5%) and five levels of food/microorganism ratio (A/M) (0.3, 0.5, 1.0, 1.5 and 1.7) were tested. The results of the batch tests did not indicate a significant effect for the response variables: accumulated CH<sub>4</sub> yield and accumulated CH<sub>4</sub> production. However, the R1, R10 and R7 reactors demonstrated better efficiency in the conversion of organic matter into biogas, with yields of 0.83; 0.80 and 0.71 L CH<sub>4</sub>/g SV added respectively for each reactor.

**Keywords:** Agroindustry. Wastewater treatment. Methane. Anaerobic digestion.

### INTRODUCTION

In 2023, Brazil was the world's second-largest producer of chicken meat and the largest exporter, with Paraná accounting for 39.47% of the volume slaughtered in the

<sup>1</sup> Master's Degree in Graduate Program in Agricultural Engineering, UNIOESTE, Cascavel campus

<sup>2</sup> Professor in the Graduate Program in Agricultural Engineering, UNIOESTE, Cascavel campus

<sup>3</sup> Professor in the Graduate Program in Agricultural Engineering, UNIOESTE, Cascavel campus

<sup>4</sup> Ph.D. in the Graduate Program in Agricultural Engineering, UNIOESTE, Cascavel campus

<sup>5</sup> Ph.D. in the Graduate Program in Agricultural Engineering, UNIOESTE, Cascavel campus

<sup>6</sup> Ph.D. in the Graduate Program in Agricultural Engineering, UNIOESTE, Cascavel campus

<sup>7</sup> Ph.D. in the Graduate Program in Agricultural Engineering, UNIOESTE, Cascavel campus

<sup>8</sup> Professor of Analytical Chemistry at the Department of Engineering and Exact Sciences at UFPR, Palotina campus, PR

<sup>9</sup> Undergraduate student in Bioprocess Engineering and Biotechnology, UFPR, Palotina campus, PR



country (ABPA, 2024). The growth and expansion of poultry activity in the State of Paraná are associated with the generation of effluents with a high organic load during the processing of animal protein.

The increase in chicken meat production in Brazil is one of the factors that contribute to the generation of liquid effluents, considering that the amount of water generated per slaughtered bird can vary from 15 to 30 liters. In addition, there is the contribution of water used in the cleaning of industrial facilities and equipment. In addition to the large volumes of effluents generated, they present heterogeneity, consisting of organic matter, nutrients, solids and oils and greases. (KUSHWAHA et al., 2010; THEBALDI et al., 2011, DALLAGO et al., 2012). Usually, the treatment process employed is composed of physicochemical flotation, followed by a biological system, which can be composed of anaerobic ponds, biodigesters, aerated ponds and/or activated sludge systems (HABCHI et al, 2024; FAGNANI, 2023; BUSTILLO-LECOMPTE; MEHRVAR, 2017).

Flotation sludge (LF) is one of the residues resulting from the physical-chemical treatment stage of the liquid effluent generated in the chicken slaughtering processes. Air is injected into the flotillator by diffusers, producing microbubbles that, through the upward flow, are responsible for carrying a fraction of the solids contained in the wastewater to the upper surface of the tank. Then, a mechanical scraper removes the flotated material, which is usually sent to a cooking unit at a temperature of 95 °C. After cooking, the sludge is sent to three-phase centrifuges (tridecanter) (FAGNANI, 2023; RESTREPO, 2019).

Anaerobic digestion has been pointed out in the literature as a sustainable technology for the stabilization of flotater sludge, but the monodigestion of this residue may be related to toxicity due to the presence of ammonia and excess fats (SALEHIYOUN et al. 2020; PAGÉS-DÍAZ et al, 2015).

Recently, studies have emerged that relate improvements in process performance with co-digestion with carbon-rich waste (DAMACENO, 2022; RESTREPO, 2019). Co-digestion is carried out from mixtures of two or more substrates: biomass or waste, which complement each other synergistically, in order to favor the production of biogas. Anaerobic codigestion has advantages over the digestion of individual wastes (monodigestion), such as the dilution of toxic components or even the addition of nutrients to the medium. (MATA-ALVAREZ et al., 2014).

In this way, the use of fresh sludge from the flotator as a substrate for anaerobic digestion enables cost reduction, such as the use of steam for cooking and equipment for the dehydration of this material, as well as transport to the composting yards. This study aims at the energy use, through the anaerobic codigestion of the fresh sludge from the



flotator added to the raw effluent of a poultry slaughterhouse.

## OBJECTIVE

Evaluate the anaerobic codigestion of fresh sludge from the flotator with the raw effluent from a poultry slaughterhouse, identifying the best proportion of flotated sludge and the feed/microorganism ratio (A/M) to optimize biogas production ( $\text{CH}_4$ ).

## METHODOLOGY

The experiment was carried out at the Laboratory of Biological Reactors (LAREB). Monitoring and carrying out physicochemical analyses at the Environmental Sanitation Laboratory, both located in block H of the State University of Western Paraná, Cascavel campus.

Anaerobic co-digestion assays were performed in laboratory-scale reactors (500 mL of total volume and 300 mL of useful volume) with 200 mL of *headspace*. Operated in batch under mesophilic conditions ( $30 \pm 1$  °C). The substrates used came from the Effluent Treatment Station (ETE) of a poultry slaughterhouse, located in the western region of Paraná. They are: 1) fresh sludge from the flotator and 2) raw effluent. Each of the samples was diluted based on the COD of the substrate mixture and inoculated with anaerobic sludge standardized to a concentration of  $2000 \text{ mg L}^{-1}$  of SSV. (NING et al., 2018).

The reactors were manually stirred once a day, to increase the contact between the microorganisms and the substrate. Before sealing the flasks, the oxygen was purged by bubbling with gaseous nitrogen (pressure of 5 psi, for 5 minutes), ensuring anaerobic inside the reactor. Thus, Table 6 shows the percentages of raw effluent and fresh sludge from the flotator and the A/M values for each of the DCCR treatments.

**Table 1** Percentages of fresh flotograph sludge and A/M values of DCCR treatments

Treatments	A/M Ratio	Fresh sludge content of the flotator (% v/v)
R1	0,5	20
R2	1,0	30
R3	1,5	40
R4	1,5	40
R5	1,0	30
R6	1,0	30
R7	0,3	15,9
R8	1,7	43,5
R9	1,0	30
R10	1,0	30
R11	1,0	30

Legend: A: food; M: microorganism.



The COD of each of the treatments was calculated based on the COD of the substrate mixture (LF+EB), where each treatment represented a content of the fresh sludge of the flotator added. The reactors were inoculated with 10% inoculum (v/v) 30 ml. The alkalinity of the mixtures was adjusted to 0.5 gNaHCO<sub>3</sub>/influent cod and the assay lasted 108 days.

Biogas volume was measured daily using a digital pressure gauge (model HT-1890; maximum pressure of 7030.7 mmH<sub>2</sub>O; operating temperature of 0 to 50°C) and plastic syringe. The digital manometer was used to measure the pressure inside the reactor and the volume collected in the syringe was obtained by equalizing this pressure with the atmospheric pressure. Biogas production was monitored until the daily volume was less than 1% of the accumulated volume, based on the criteria established by the VDI 4630 (2006) standard. The parameters used for determination were obtained at the end of the experiment and the response variables: accumulated CH<sub>4</sub> production (L) and CH<sub>4</sub> yield (L CH<sub>4</sub>/g SV added)

## DEVELOPMENT

### EFFECTS OF INDEPENDENT VARIABLES ON CRSD

The analysis of the influence of the factors aimed to evaluate the best conditions for the anaerobic codigestion process of the fresh sludge from the flotator with the raw effluent of a poultry slaughterhouse in the investigated ranges.

**Table 2** - Planning matrix (DCCR) with the factors and results obtained for the response variables: accumulated production of CH<sub>4</sub> (L) and CH<sub>4</sub> yield (L CH<sub>4</sub>/g SV added)

Reactor	Factors (actual values)		Response variables	
	Fresh floton sludge (%, v/v)	Ratio (A/M) (cod/gSSV)	Cumulative production CH <sub>4</sub> (L)	Yield CH <sub>4</sub> (L CH <sub>4</sub> /g SV added)
R1	-1 (20)	-1 (0,5)	0,36	0,83
R2	+1 (40)	-1 (0,5)	0,15	0,13
R3	-1 (20)	+1 (1,5)	0,11	0,10
R4	+1 (40)	+1 (1,5)	0,57	0,53
R5	-1,414 (15,9)	0 (1)	0,15	0,22
R6	+1,414 (43,5)	0 (1)	0,22	0,26
R7	0 (30)	-1,414 (0,3)	0,31	0,71
R8	0 (30)	+1,414 (1,7)	0,09	0,07
R9	0 (30)	0 (1)	0,29	0,44
R10	0 (30)	0 (1)	0,52	0,80
R11	0 (30)	0 (1)	0,30	0,29

Table 2 presents the planning matrix, obtained by applying the Central Rotational Composite Design (DCCR), with the respective response variables. The food/microorganism ratios between 0.5 and 1 gCOD/gSSV provided the highest yields of CH<sub>4</sub> (L CH<sub>4</sub>/g SV added) in the final phase, being 0.83 CH<sub>4</sub> (L CH<sub>4</sub>/g SV added) for the R1



reactor and 0.80 CH<sub>4</sub> (L CH<sub>4</sub>/g SV added) for the R10 reactor.

In practice, the A/M ratio is not a parameter that is strictly monitored in the industry, this ratio may have affected the estimated effects of the DCCR, since none was significant (beyond the average). Treatments with a higher W/M ratio resulted in higher CH<sub>4</sub> production (L) and higher CH<sub>4</sub> yield (L CH<sub>4</sub>/g SV added). In particular, treatments R1, R4, R7 and R10 showed the highest values of accumulated CH<sub>4</sub> production.

Compared to the cumulative methane yield of lipid-rich pig slaughterhouse residues (SSW) for initial loads of 10–40 g SV/L increased rapidly to over 800 mL/g SV at A/M ratios of 0.7 and 1 during the first 25 days. However, it took more than 35 days for the cumulative methane yield to reach 800 mL/g SV at an A/M ratio of 1.5, and 50 days were required for A/M ratios of 2 and 2.5 with initial loads of 10-40 g SV/L. These results showed that higher A/M ratios prolonged the conversion of lipid-rich pig slaughterhouse residues to methane, while lower A/M ratios of 0.7 and 1 promoted the conversion of lipid-rich pig slaughterhouse waste to methane in less than 25 days (LATIFI et al., 2019).

The highest yields of biogas and methane in the experiments reported by Ning et al., (2018) were by 0.631 m<sup>3</sup>/kg-SV added to the batch reactors and 0.462 m<sup>3</sup>/kg-SV added to the digester on a larger scale, obtained with the removal of 66% of volatile solids (SV). The optimized parameters obtained in the first phase were also used for verification on a larger scale (20 liters), where the biogas and methane yields found were 0.574 and 0.402 m<sup>3</sup> /kg-SV added; respectively. The results showed that the optimal anaerobic digestion of slaughterhouse waste in a 20-liter digester can lead to 63% SV removal and 88% reduction of SVChemical oxygen demand(COD) over a 42-day retention period. In addition, the substrates used in this experiment can be used on a larger scale in order to verify their behavior in terms of SV removal and accumulated CH<sub>4</sub> production (NING et al., 2018).

The regression for the data showed R<sup>2</sup>=0.38, representing 38% of the variation in production efficiency. The data related to the results of the analysis of variance (ANOVA) of the model are presented in Table 2.

**Table 2** - Analysis of Variance (ANOVA)

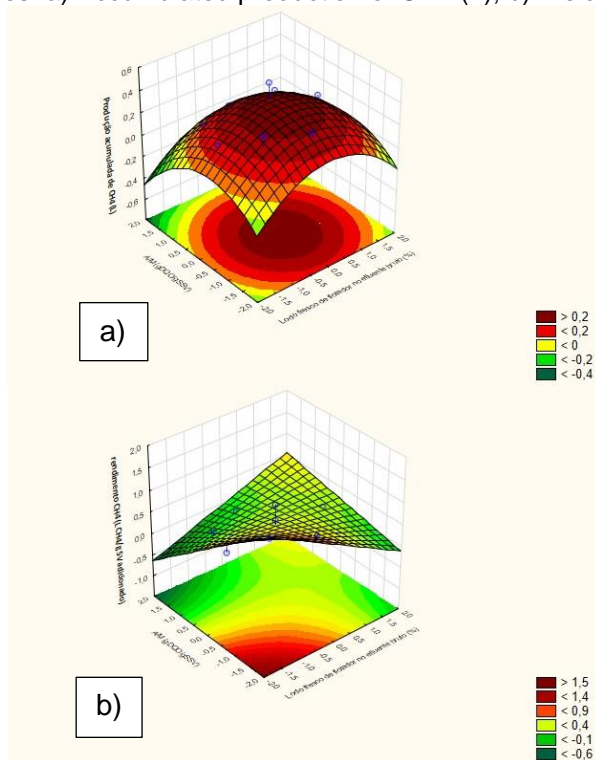
Source of variation	Quadratic Sum	Degrees of Freedom	Medium Square	Fcal	F tab
Regression	0,06	2	0,03	2,5	4,46
Residue	0,1	8	0,01		
Pure error	0,06	7	0,01		
Total	0,16	10			

ANOVA indicated that the model obtained cannot be considered predicted, since for a confidence level of 10%, the F test indicated a calculated F lower than the tabulated F.

Even so, from these results, response surfaces were generated in order to verify the experimental regions that have the best responses, represented in Figure 1.

However, when the accumulated production and yield variables are related (Figure 1 a), it is verified that the best production occurs close to the central points, as indicated in the graph. And that the income variable does not have a significant effect with a confidence interval of 90% ( $p < 0.10$ ).

**Figure 1** - Response surfaces. a) Accumulated production of CH<sub>4</sub> (L); b) Yield of CH<sub>4</sub> (L CH<sub>4</sub>/g SV added)



## MODELING METHANE PRODUCTION

The effect of the addition of fresh sludge from the flotator was also evaluated by calculating the reaction performance parameters for the response variables: maximum CH<sub>4</sub> production (P), maximum specific velocity (R<sub>m</sub>), and lag phase duration or lag time, ( $\lambda$ ), using the modified Gompertz model (ZWIETERING et al., 1990).

According to Gompertz's model, a maximum final production of 462586.84 mL/g SSV was estimated for the R4 reactor, and 72095.63 mL/g SSV for the R6 reactor. The reactors under study referring to DCCR that did not present lag phase time were R3, R5 and R8. Labatut et al. (2010) evaluated that in each phase of anaerobic digestion it would be possible to observe a different kinetics, considering the characteristics of the substrates and the possibility of converting substrates into different intermediate products.

Table 3 presents the kinetic parameters obtained from the aforementioned model, in the planning matrix, constructed by the application of the DCCR.



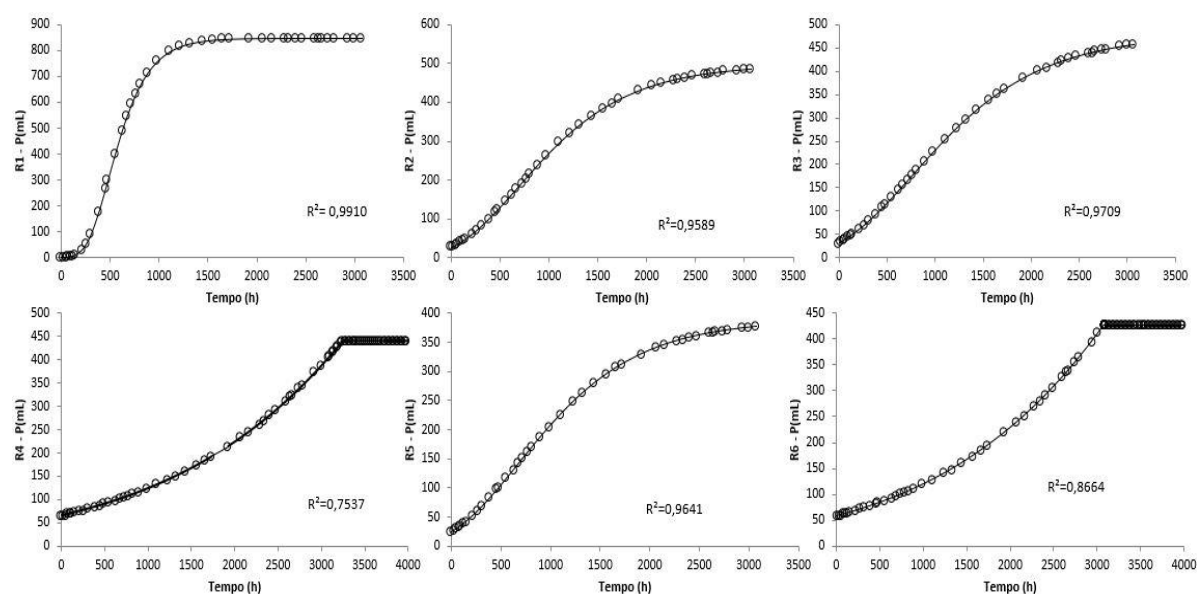
**Table 3** - Planning matrix (DCCR) with the real factors and the results of the kinetic parameters obtained from the modified Gompertz model

Factors (actual values)			Kinetic parameters		
Reactor	Fresh Flotator Sludge (%)	Ratio (A/M) (cod/gSSV)	Cumulative production CH4 (L)	Rm (mL/h)	$\lambda$ (h)
R1	-1 (20)	-1 (0,5)	0,36	1,38	262,40
R2	+1 (40)	-1 (0,5)	0,15	0,29	49,87
R3	-1 (20)	+1 (1,5)	0,11	0,23	0,00
R4	+1 (40)	+1 (1,5)	0,57	12,73	15796,94
R5	-1,414 (15,9)	0 (1)	0,15	0,21	0,00
R6	+1,414 (43,5)	0 (1)	0,22	2,82	9037,88
R7	0 (30)	-1,414 (0,3)	0,31	1,02	161,68
R8	0 (30)	+1,414 (1,7)	0,09	0,15	0,00
R9	0 (30)	0 (1)	0,29	0,45	252,74
R10	0 (30)	0 (1)	0,52	0,46	519,02
R11	0 (30)	0 (1)	0,30	0,72	105,14

Figures 2 and 3 show the estimates made for the adjustment of the modified Gompertz model, obtained in the production of methane from the co-digestion of fresh flotation sludge and raw effluent in the batch test (DCCR) for reactors R1 to R11.

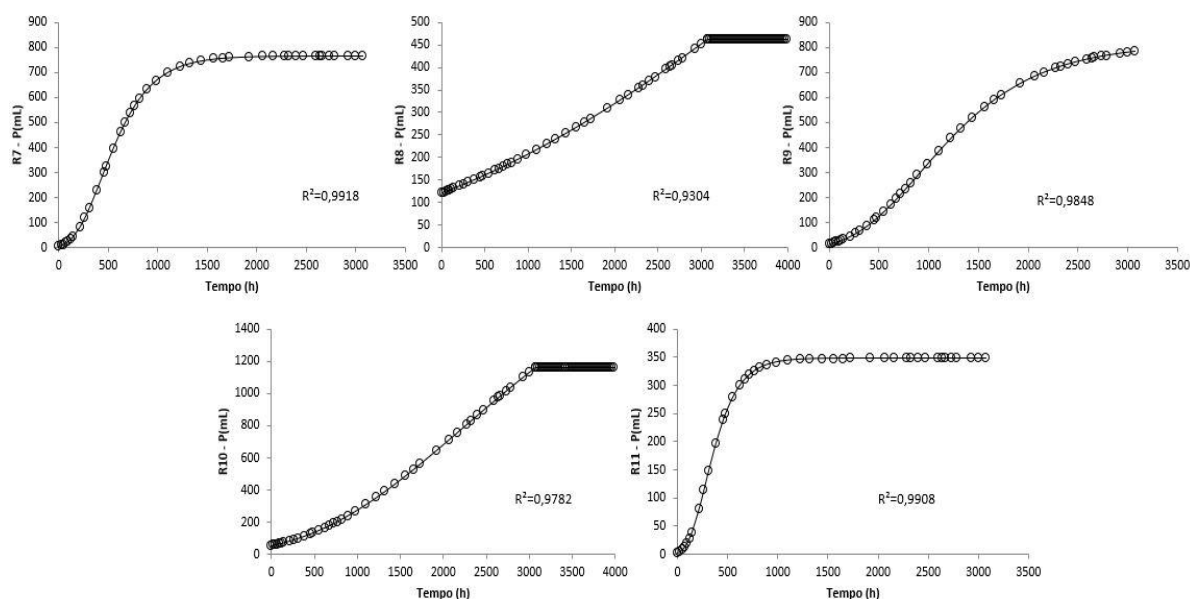
**Figure 2** - Estimates for the adjustment of the modified Gompertz model, obtained in the production of methane from the co-digestion of fresh flotation sludge and raw effluent in the batch test (DCCR) for reactors R1 to R6.

**Grades:** R1 (34% EB + 65% LF, A/M 0.5), R2 (75.9% EB + 24% LF, A/M 0.5), R3 (35% EB + 65% LF, A/M 1.5), R4 (75.9% EB + 24% LF, A/M 1.5), R5 (26.7% EB + 73.3% LF, A/M 1), R6 (83.2% EB + 16.8% LF, A/M 1).





**Figure 3** - Estimates for the adjustment of the modified Gompertz model, obtained in the production of methane from the co-digestion of fresh flotater sludge and raw effluent in the batch test (DCCR) for reactors R7 to R11. **Grades:** R7 (55.4% EB + 44.6% LF, A/M 0.3), R8 (55.4% EB + 44.6% LF, A/M 1.7), R9, R10 and R11 (55.4% EB + 44.6% LF, A/M 0.1).



However, it was observed that the modified Gompertz model was not adequate to describe the accumulated biogas production curves by presenting coefficients of determination ( $R^2$ ). Except for the R1, R7 and R11 reactors, as they showed signs of stabilization of biogas production, presenting the highest linear correlation coefficients between the treatments.

Ware and Power (2016) in a study on poultry slaughterhouse waste also demonstrated that cumulative methane curves can emerge in various forms and it was possible to classify them into three groups: L-shaped, elongated S-shaped, and step curves. Another aspect mentioned by these authors was the importance of not attributing the validity of the models only to the  $R^2$  values, in comparison with the logistic and logistic models. R4 and R6 and in Figure 3 the reactor R10.

## FINAL CONSIDERATIONS

Considering the results obtained, in relation to the potential of methane production in the codigestion of fresh flotation sludge and raw effluent from a poultry slaughterhouse in batch reactors, it can be concluded that: The statistical analysis indicated that the model obtained cannot be considered predicted for a confidence level of 10%. However, the behavior of the response variables in the quadratic models of the accumulated  $\text{CH}_4$  production (L) and  $\text{CH}_4$  yield (L  $\text{CH}_4/\text{g}$  SV added) based on the independent variables (fresh flotogen sludge, v/v and A/M ratio (gCOD/gSSV)) indicated higher values of accumulated  $\text{CH}_4$  production among the mixtures that contained a higher percentage of



fresh flocculent sludge.

The results indicate that the best A/M ratio to optimize methane yield is between 0.3 and 1, with emphasis on 0.5 gCOD/gSSV. In addition, the R1, R10 and R7 reactors demonstrated better efficiency in converting organic matter into biogas, with yields of 0.83; 0.80 and 0.71 L CH<sub>4</sub>/g SV added respectively for each reactor.

### **ACKNOWLEDGMENTS**

To the professors and colleagues of the Graduate Program in Agricultural Engineering PGEAGRI and the Coordination for the Improvement of Higher Education Personnel (CAPES).



## REFERENCES

1. ABPA - Brazilian Association of Animal Protein. (2024). \*Annual report 2024\*. ABPA.
2. APHA, AWWA, & WEF. (2017). \*Standard methods for examination of water and wastewater\* (23rd ed.). American Public Health Association; American Water Works Association; Water Environmental Federation.
3. Bustillo-Lecompte, C. F., & Mehrvar, M. (2017). Treatment of actual slaughterhouse wastewater by combined anaerobic–aerobic processes for biogas generation and removal of organics and nutrients: An optimization study towards a cleaner production in the meat processing industry. \*Journal of Cleaner Production, 141\*, 278–289.
4. Cirne, D. G., Paloumet, X., Björnsson, L., Alves, M. M., & Mattiasson, B. (2007). Anaerobic digestion of lipid-rich waste – effects of lipid concentration. \*Renewable Energy, 32\*(6), 965–975.
5. Damaceno, F. M., Chiarellotto, M., Restrepo, J. C. P. S., Buligon, E. L., Mendonça Costa, L. A., Lucas Junior, J., & Costa, M. S. S. M. (2019). Anaerobic co-digestion of sludge cake from poultry slaughtering wastewater treatment and sweet potato: Energy and nutrient recovery. \*Renewable Energy, 133\*, 489–499.
6. Damaceno, F. M., Bastos, J. A., Lima Alino, J. H., Remor, P. V., Silva de Mendonça Costa, M. S., & Edwiges, T. (2022). Effect of thermal, alkaline, and thermal-alkaline pretreatments on the anaerobic digestion of poultry slaughterhouse waste. \*Environmental Engineering & Management Journal, 21\*(5).
7. Elsayed, M., Andres, Y., Blel, W., Gad, A., & Ahmed, A. (2016). Effect of vs organic loads and buckwheat husk on methane production by anaerobic co-digestion of primary sludge and wheat straw. \*Energy Conversion and Management, 117\*, 538–547.
8. Enokida, C. H., Tap paro, D. C., Before, F. G., Steinmetz, R. L. R., Magrini, F. E., Sophiatti, I. V. M., & Kunz, A. (2025). Anaerobic codigestion of livestock manure and agro-industrial waste in a CSTR reactor: Operational aspects, digestate characteristics, and microbial community dynamics. \*Renewable Energy, 238\*, 121865.
9. Fagnani, K. C. (2017). \*Comparison of the energy potential of the sludge generated in the physicochemical treatment of effluents from poultry slaughter using different coagulants\* [Master's dissertation, Federal University of Paraná].
10. Fagnani, K. C. (2023). \*Energy valorization of sludge from effluent treatment system of the slaughtering and meat processing industry via anaerobic codigestion\* [Doctoral dissertation].
11. Habchi, S., Pecha, J., Šánek, L., Karouach, F., & El Bari, H. (2024). Sustainable valorization of slaughterhouse waste through anaerobic digestion: A circular economy perspective. \*Journal of Environmental Management, 366\*, 121920.
12. Latifi, P., Karrabi, M., & Danesh, S. (2019). Anaerobic co-digestion of poultry slaughterhouse wastes with sewage sludge. \*Renewable and Sustainable Energy Reviews, 107\*, 288–296.



13. Latifi, P., Karrabi, M., & Shahnava, B. (2021). Estimating the potential of energy generation by anaerobic digestion of slaughterhouse wastes toward sustainable waste management strategy: A case study. *\*Energy Sources, Part A: Recovery, Utilization, and Environmental Effects\**, 1–12.
14. Mallmann, L. S. (2013). *\*Methane production potential of cattle submitted to a diet supplemented with wet brewery waste\** [Doctoral dissertation, State University of Western Paraná].
15. Ning, Z., Zhang, H., Li, W., Zhang, R., Liu, G., & Chen, C. (2018). Anaerobic digestion of lipid-rich swine slaughterhouse waste: Methane production performance, long-chain fatty acids profile and predominant microorganisms. *\*Bioresource Technology\**, 269, 426–433.
16. Oliveira, A. B. D. M., Orrico, A. C. A., Junior, M. A. P. O., Silva Sunada, B., & Centurion, S. R. (2015). Anaerobic biodigestion of poultry slaughterhouse effluent. *\*Ceres\**, 58(6).
17. Pagés-Díaz, J., Westman, J., Taherzadeh, M. J., Pereda-Reyes, I., & Horváth, I. S. (2015). Semi-continuous co-digestion of solid cattle slaughterhouse wastes with other waste streams: Interactions within the mixtures and methanogenic community structure. *\*Chemical Engineering Journal\**, 273, 28–36.
18. Ragasri, S., & Sabumon, P. C. (2023). A critical review on slaughterhouse waste management and framing sustainable practices in managing slaughterhouse waste in India. *\*Journal of Environmental Management\**, 327, 116823.
19. Restrepo, J. C. P. S. (2019). *\*Anaerobic codigestion of chicken slaughter flotator sludge and sugarcane juice\** [Master's dissertation, State University of Western Paraná].
20. Restrepo, J. C. P. S., Damaceno, F. M., Chiarellotto, M., Bofinger, J., Niedzialkoski, R. K., Mendonça Costa, L. A., & Mendonça Costa, M. S. S. (2022). Sugarcane juice improves energy production in the anaerobic co-digestion with flotation sludge from broiler slaughter. *\*Fuel\**, 330, 125577.
21. Salehiyoun, A. R., Di Maria, F., Sharifi, M., Norouzi, O., Zilouei, H., & Aghbashlo, M. (2020). Anaerobic co-digestion of sewage sludge and slaughterhouse waste in existing wastewater digesters. *\*Renewable Energy\**, 145, 2503–2509.