ENHANCING METHANE PRODUCTION IN LOW-COST TUBULAR ANAEROBIC DIGESTERS USING STRUCTURAL SUPPORT MEDIA

M.C. Gil-Rosales[1,2], E. Diaz[1,3], J. Marti-Herrero[4,5], A.F. Mohedano[1,3], M.A. de la Rubia[1,3]*

[1] *Departamento de Ingeniería Química, Universidad Autónoma de Madrid, 28049, Madrid, España*
[2] *IFAPA Centro La Mojonera, Paraje San Nicolás, Carretera de Cádiz, salida 809, 04745 La Mojonera, Almería, España*
[3] *Institute for Advanced Research in Chemistry, Universidad Autónoma de Madrid, 28049, Madrid, España*
[4] *Centre Internacional de Mètodes Numèrics en Enginyeria (CIMNE), Rambla Sant Nebridi 22, 08222, Terrassa, Barcelona, España*
[5] *Biomass to Resources Group, Universidad Regional Amazónica Ikiam, Vía Tena-Muyuna, Km.7, Tena, Napo, Ecuador*

** Corresponding author's email address: angeles.delarubia@uam.es*

Highlights

- Psychrophilic anaerobic digestion of swine manure produced methane enriched biogas (~80%).
- The use of support materials enhanced the performance of swine manure digestion.
- The digester with plastic support reached the highest methane yield, 496 mL CH_4 STP·g^{-1} VS.

Introduction

Livestock farming stands out as a major contributor to environmental degradation within the agricultural sector. Only in 2023 it was responsible for emitting approximately 377 million t CO_2 equivalent in the European Union (EU) (EEA, 2023). Beyond greenhouse gas emissions, this activity also leads to water pollution, unpleasant odors, the spread of pathogenic microorganisms, and the release of emerging contaminants, all of which have a significant ecological impact. Over 20% of surface water bodies and nearly 30% of groundwater in Europe suffer from diffuse pollution due to the application of manure on agricultural land, mainly from nutrients and pesticides (EEA, 2023). These effects are particularly severe in areas of intensive animal farming, where large numbers of animals are raised in confined environments.

In the EU, an estimated 90% of livestock manure —around 1,300 million t y^{-1}— is spread on agricultural soils, yet only about 30% ($4·10^8$ t annually) undergoes proper composting (Köninger et al., 2021). Effective composting typically requires mixing the manure with lignocellulosic materials to enhance the carbon-to-nitrogen (C/N) ratio. Moreover, achieving sanitization of the final product needs to maintain high temperatures (50–70 °C), along with proper aeration and moisture control, and the full stabilization of organic matter can take up to six months. However, composting alone does not adequately address the management of the liquid fraction of manure, which remains a particularly challenging and pollutant-rich by-product (Ipiales et al., 2024).

Conventional anaerobic digestion of untreated animal manure using continuously stirred tank reactors (CSTR) under mesophilic conditions is generally inefficient because requires a heating system, the C/N ratio is unbalanced and the presence of substances such as ammonia (NH_3-N), pharmaceuticals, hormones, and heavy metals can inhibit the process. These factors limit both organic matter degradation and methane generation (Zahedi et al., 2022). Nonetheless, psychrophilic tubular digesters have been widely implemented in Latin America for several decades, with satisfactory results for the treatment of agricultural waste and the production of biogas (Garfi et al., 2016). These digesters, made from plastic geomembranes, are placed semi-buried in the soil, do not require active heating or agitation systems, and can accumulate biogas in the dome or store it in a separate geomembrane system (Marti-Herrero et al., 2014). These tubular digesters have already demonstrated their feasibility at full scale (TRL 9) to treat pig slurry, produce biogas, and recover nutrients (Jaimes-Estevez et al., 2021). However, there are no experiences with this technology in Europe, where the most widely used type of anaerobic digester is the complete mix, operating in the mesophilic temperature range (35°C).

The objective of this research is to study the effect of hydraulic retention time as well as the use of different kinds of support (organic and plastic) on the performance of psychrophilic tubular digesters for treating the aqueous fraction of swine manure .

Material and Methods

Three tubular reactors (R1, R2, and R3) made of methacrylate, 100 cm long, 10.77 cm internal diameter were used to carry out experiments. The working volume of these digesters is 7 L and the headspace 2.1 L. The inlet and outlet valves, as well as the fittings and connections, are made of 1" PVC. The 0.25" outlet port is connected to a Tedlar bag where the biogas stream was stored. The reactors were kept at room temperature (22-27 ºC) and monitored daily. R1 was operated without support, in R2 tubular plastic pieces (14 mm in radius and 99 mm in length) and in R3 wood chips (average length of 54 mm) were used as support materials. The addition of these materials in R2 and R3 resulted in an extra support surface area of 0.31 m^2, representing a 2.5-fold increase relative to the internal surface area of the control digester (R1) enabling a comparative assessment of the performance of tubular reactors operating with and without different media support.

The digesters start-up was carried out in discontinuous mode, using the aqueous fraction of swine manure as inoculum. Its main characteristics are collected in Table 1. The headspace of the digesters was gassed with N_2 for 3 min to ensure anaerobic conditions. After the start-up (7 days), the reactors were fed once a day with aqueous fraction of swine manure (feed, Table 1) at a hydraulic retention time (HRT) of 20 d. The steady state was confirmed by checking the effluent characteristics, and after a period equivalent to three times the HRT. Analyses were conducted for five consecutive days after reaching each steady state. Hydraulic retention times of 15 and 10 d will be also tested. Both the inoculum and the effluent from the reactors have been characterized by determining pH (Crison 20 Basic pH meter), alkalinity (method 2320B, APHA, 2005); total solids (TS) and volatile solids (VS) (methods 2540B and 2540E, respectively, APHA, 2005); total chemical oxygen demand (TCOD) and soluble COD (SCOD) (according to Raposo et al. (2008) and 5220D APHA, (2005), respectively). Total ammonia nitrogen (4500D method (APHA, 2005)), and volatile fatty acids (VFAs) via GC-FID (Diez et al., 2024). In addition, the volume of biogas was measured using a Hamilton 1 L Super Syringe Model S1000 and expressed at standard temperature and pressure (STP: 273 K, 1 bar). The biogas composition was determined using a GC (Shimadzu GC-2014) equipped with a thermal conductivity detector and a Carboxen 1010 PLOT fused silica capillary column.

Table 1. Characterization of swine manure.

Parameter	Inoculum	Feed
pH	7.3 (0.01)	7.7 (0.01)
Alkalinity (g $CaCO_3 \cdot L^{-1}$)	4.7 (0.5)	6.7 (0.6)
Total solids (g·kg^{-1})	7.2 (0.1)	12.8 (0.7)
Volatile solids (g·kg^{-1})	3.4 (0.1)	6.8 (0.4)
Total COD (g $O_2 \cdot L^{-1}$)	17.5 (0.4)	14.3 (0.4)
Soluble COD (g $O_2 \cdot L^{-1}$)	4.0 (0.1)	6.9 (0.1)
Total Kjeldahl Nitrogen (mg·L^{-1})	1550 (152)	1800 (10)
Ammoniacal Nitrogen (mg·L^{-1})	733 (70)	1567 (10)
Volatile fatty acids (mg COD ·L^{-1})	4531 (217)	4279 (169)

Results and Discussion

Table 2 shows the pH, alkalinity and ammoniacal nitrogen of the effluents. The pH remained close to 8, related to the pH of the influent and the high alkalinity level (> 7.0 g $CaCO_3 \cdot L^{-1}$). These high alkalinity values were also associated with high concentrations of ammoniacal nitrogen (≥ 1400 mg·L^{-1}). However, despite these elevated levels, no signs of process inhibition were observed.

Table 2. Characterization of digesters effluent.

Parameter	R1	R2	R3
pH	7.9 (0.0)	7.9 (0.0)	7.9 (0.0)
Alkalinity (g $CaCO_3 \cdot L^{-1}$)	7.2 (0.2)	7.4 (0.2)	7.2 (0.3)
Ammoniacal Nitrogen (mg·L^{-1})	1508 (113)	1476 (110)	1370 (166)

Standard deviation is reported in parenthesis

Fig. 1a shows TCOD and SCOD concentrations for each reactor under steady-state conditions for HRT of 20 d, as well as total VFA, expressed as mg COD·L^{-1}. Total solids removal, considering the feed content (Table 1) was slightly higher for R2 and R3 (45.1%) than for R1 (43.6%). Similarly, the VS removal (Fig. 1b) showed a little better behavior for R2 and R3 (67.7%) than for R1 (64.2%). The ratio VS/TS of the feed (0.53), clearly decreased after AD until 0.33 for R1 and 0.31 for R2 and R3, showing that easily biodegradable matter was removed. The higher VFA concentration determined for R1 (562 (6) mg COD·L^{-1}), also indicates a worse performance of R1 than the observed for R2 and R3 (324 (3), 202 (4) mg COD·L^{-1}, respectively).

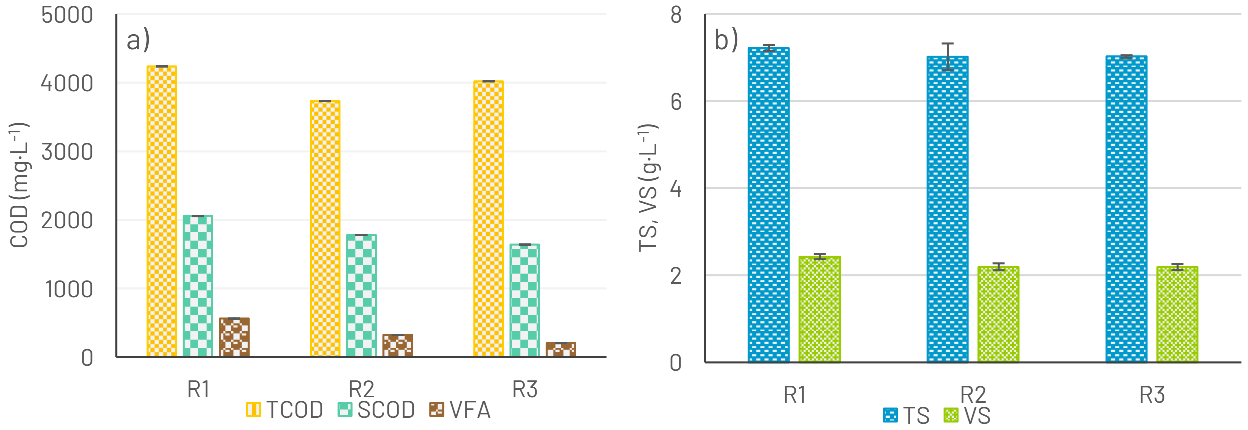

Figure 1. Total and soluble COD and total VFA (a), Total and volatile solids (b).

Figure 2 illustrates the daily biogas production and methane yield, expressed as mL CH_4·g^{-1} VS, for the digesters operated with and without support materials. The highest methane yield was achieved in the digester containing plastic support, reaching 496 (35) mL CH_4 STP·g^{-1} VS, a 19% higher than the control. Notably, the biogas from the supported digesters exhibited a high methane content —up to 82%— which contributed to the higher methane yield observed in reactor R3 compared to R1, despite the fact that R1 produced a greater overall volume of biogas.

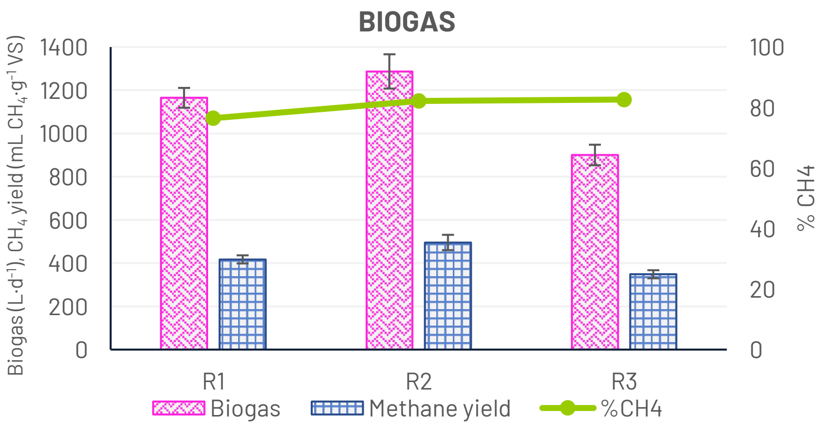

Figure 2. Biogas composition and methane yields.

Conclusion

The incorporation of support materials into psychrophilic tubular anaerobic digesters for swine manure treatment positively influenced both biogas quality and methane yield. Among the configurations tested, the digester supplemented with plastic support achieved the highest methane yield (496 (35) mL CH_4 STP·g^{-1} VS), highlighting the role of additional surface area in promoting microbial activity and enhancing process efficiency. Moreover, the reactors operated under stable conditions, despite elevated ammoniacal nitrogen levels (≥ 1400 mg·L^{-1}), which did not lead to process inhibition. This suggests a robust system with good resilience and adaptability under the tested conditions. Overall, the results highlight the potential of structural support, especially plastic media, as a promising strategy to improve the performance, stability, and methane productivity of tubular anaerobic digesters treating swine manure in low-temperature environments.

Acknowledgements

This work was funded through the project PP.PEI.IDF2023030.001 – Development of Treatment and Agricultural Valorization Techniques for Intensive Pig Slurry in Eastern Andalusia (AgroPuriTech). Strategic Projects and Institutional Demand Action. IFAPA. FEDER.

References

APHA, 2005. Standard Methods for the Examination of Water and Wastewater, twenty-first ed. American Public Health Association, Washington. DC., USA

EEA, Trends and Projections in Europe 2023, Publications Office of the European Union.

Garfí, M, Martí-Herrero, J.A., Garwood, A.I., Ferrer, I. 2016. Household anaerobic digesters for biogas production in Latin America: A review. Renew Sust Energ Rev 60, 599-614.

Ipiales, R.P., Díaz, E., Mohedano, A.F., de la Rubia, M.A. 2024. Material and energy recovery from animal manure by hydrothermal carbonization, in: Reference Module in Materials Science and Materials Engineering, Elsevier. https:// doi.org/10.1016/B978-0-443-29210-1.00008-X.

Jaimes-Estévez, J., Zafra G., Martí-Herrero J., Pelaz G., Morán A., [...], Escalante Hernández H. 2021. Psychrophilic Full scale tubular digester operating over eight years: Complete performance evaluation and microbiological population. Energies, 14, 151.

Köninger, J., Lugato, E., Panagos, P., Kochupillai, M., Orgiazzi, A., Briones, M.J.I. 2021. Manure management and soil biodiversity: towards more sustainable food systems in the EU, Agric. Syst. 194, 103251, https://doi.org/10.1016/j. agsy.2021.103251.

Martí-Herrero, J. Chipana, M. Cuevas, C. Paco, G.V. Serrano, V. Zymla B. [...], A. Gamarra. 2014. Low-cost tubular digesters as appropriate technology for widespread application: Results and lessons learned from Bolivia. Renew Energ, 71, 156-165.

Raposo, F., De la Rubia, M.A., Borja, R., Alaiz, M., 2008. Assessment of a modified and optimised method for determining chemical oxygen demand of solid substrates and solutions with high suspended solid content. Talanta 76, 448–453. https://doi.org/ 10.1016/j.talanta.2008.03.030.

Zahedi, S., Gros, M., Petrovic, M., Balcazar, J.L., Pijuan, M. 2022. Anaerobic treatment of swine manure under mesophilic and thermophilic temperatures: fate of veterinary drugs and resistance genes, Sci. Total Environ. 818, https://doi.org/ 10.1016/j.scitotenv.2021.151697.