Colegio de Postgraduados

Physical-chemical and nutritional parameters of liquid porcine effluent from a biodigester supplemented with a lagoon system

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ABSTRACT

Objetive: Determining the concentration of physical-chemical and nutritional parameters of the wastewater derived from a biodigester complemented with lagoon train.

Metodology: A study was carried out in the CEAJAL livestock production module, 12 gestating sows, fresh solid excreta was collected manually (shovel and wheelbarrow), the lagoon-type biodigester was fed daily with two levels of organic load (CO), CO5% and CO15%. The biogas and wastewater were evaluated in four periods of 40 days each. The Influent washing water (INF) entered the biodigester, then the liquid effluent (EFL) was subjected to complementary treatment of EFL stabilization pits, Pit 2, Pit 3 and Pit 4, determining physical-chemical parameters such as TSS, pH, CTE and COD, and nutritional parameters such as NT and FT. The data were analyzed using descriptive and differential statistics.

Results: The methane content in the biogas was 59.8%; CO5% and 60.2%; CO15% ($p>0.05$). The physical-chemical parameters of INF such as SST ml/L was 67.4; CO5% and 81.3; CO15%. EFL was 23.2 and 48.0, respectively, in COD ml/L of INF was 738.7; CO5% and 1807.7; CO15%. EFL was 1444.2 and 2522.5, respectively, in NT ml/L of INF was 128.3; CO5% and 111.9; CO15%. EFL was 436.9 and 554.6, respectively.

Conclusions: Despite a lower CO, methane production is in the normal range and the physical-chemical and nutritional parameters of the wastewater as it passes into stabilization lagoons can be taken as a reference to determine the CO that should enter to the biodigester with the purpose of providing complementary treatment of the wastewater generated in pig farms.

Keywords: wastewater, pig farm, technological adoption.

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INTRODUCTION

Biodigesters have been used on pig farms for biogas production and, in the last decade, have served as a wastewater treatment method (Cubillos-Sierra *et al.*, 2018). The efficiency of a biodigester used for wastewater treatment can be determined by the concentration of physical-chemical and nutritional parameters. In recent years, microbiological aspects have also been considered (Penafiel *et al.*, 2021). However, in many cases, the levels of Organic Load (OL), Hydraulic Retention Times (HRT), and the complementary treatments of each of the byproducts derived from a biodigester are omitted (Galindo-Barboza *et al.*, 2020).

Pigs in confinement farms generate different types of organic waste. Regardless of the level of farm technology, these wastes represent a contamination risk due to the lack of utilization of all the nutrients consumed in their feed ration. The quantity and quality of excreta depend on the diet, animal age, and facility design (Kebreab *et al.*, 2016). Therefore, the accumulated excreta used in crop field fertilization without prior treatment has led to increased levels of nitrogen and phosphorus in the soil. Additionally, since most of the piles or pits containing manure on farms are exposed to the open air, rain and wind dissolve the soluble nutrients. At the same time, ammonia emissions into the environment increase, resulting in a stronger odor, as well as the infiltration of nitrites and nitrates into nearby water bodies, a process known as eutrophication (Pinos-Rodríguez *et al.*, 2012; Domínguez-Araujo *et al.*, 2023).

The establishment of a biodigester should be considered within an integrated organic waste management program, which helps mitigate environmental damage and benefits large, medium, and small farms in environmental, technological (Magnusson *et al.*, 2022), and economic (Durante-Mühl & De Oliveira, 2022) aspects.

An integrated waste management program, as a technological adoption, must consider the separation and classification of the material to be treated (solid and liquid waste) to obtain the maximum benefit from the processes (Barrera-Cardoso *et al.*, 2020). Additionally, this facilitates the selection of the process and the implementation of practical methodology (Somagond *et al.*, 2020).

The management and treatment of liquid excreta through biodigesters should be combined with other strategies such as physical, chemical, and even biological processes that are easy to adopt, compatible with biodigesters, and reasonably priced. Working synchronously, these strategies generate byproducts (organic fertilizers, biogas, and treated wastewater) for use both within and outside the farms (Domínguez-Araujo *et al.*, 2023).

Therefore, the objective of this study was to determine the physical-chemical and nutritional parameters of the liquid effluent from a biodigester fed with different organic loads, using stabilization ponds as a complementary treatment.

MATERIALS AND METHODS

Location

This study was conducted in the pig production and waste utilization module at the Central Highlands of Jalisco Experimental Field of INIFAP, in Tepatitlán de Morelos, Jalisco.

Biodigester

An anaerobic lagoon-type biodigester with a capacity of 6 m^3 was used, operating at a mesophilic temperature (32 °C) outside and maintaining an average temperature (24 °C) inside. It has a continuous flow feeding regime that aids agitation inside by gravity and pressure, with a Hydraulic Retention Time (HRT) of 30 days. Adjacent to the biodigester is the discharge tank (effluent), followed by the lagoon system, consisting of three adjacent pits for the post-treatment of the liquid effluent. This liquid undergoes decantation through the pits, with an HRT of 7 days in each pit (Figure 1).

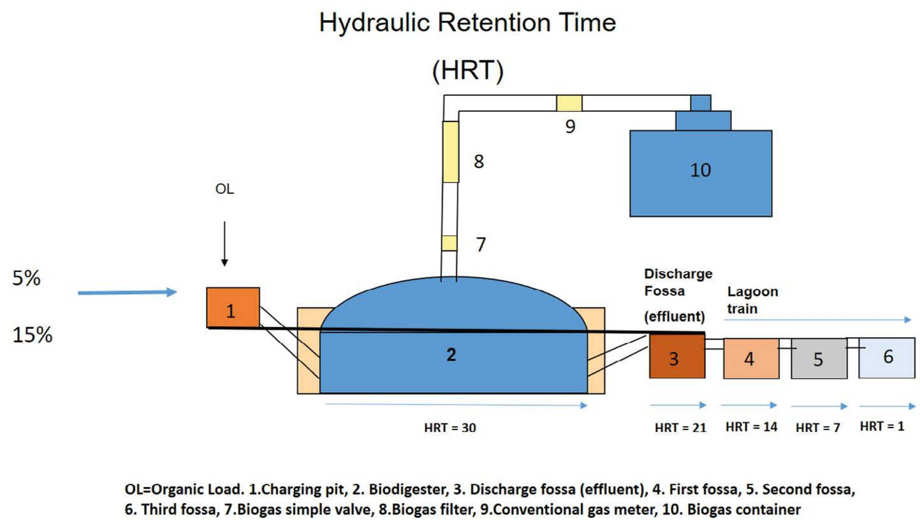

Figure 1. Schematic of the biodigester with three adjacent stabilization ponds (Image modified from Domínguez-Araujo *et al.*, 2023).

Organic Loads

From the gestation area, a total of 12 sows in production with an average weight of 220 kg, 1.8 kg of solid organic waste was excreted per day on average. These were manually collected (using a shovel and wheelbarrow) to obtain fresh excreta each day.

Once the solid excreta were removed from the pens, they were weighed to determine the organic load (OL) percentages. The excreta were placed in a 100-liter cylinder (the maximum capacity of the biodigester per day) and mixed with tap water, adjusting to achieve two OL levels: OL5% and OL15%, with a ratio of 1:9 and 1:5, respectively. The OL was then decanted into the biodigester's influent pit.

Sampled Byproducts

Biogas

The biogas is conducted from the biodigester's dome through reinforced PVC piping. At a distance of 3 meters from this point, there is a valve on the piping for obtaining a biogas sample (1 cubic decimeter).

Wastewater

Directly from the outlet pipe of the biodigester at the discharge tank and in each of the lagoons in the lagoon system, a sample of the effluent was collected in a one-liter capacity container in its liquid physical form (liquid effluent). This sample was then transferred to Imhoff sedimentation cones to determine the Total Settled Solids (TSS) of the solid fraction, and the liquid fraction was stored in 1-liter capacity bottles at a temperature of 4 °C for subsequent analysis. (Figure 1).

Sample Analysis

Biogas: Using a LANTEC biogas measurement device, the percentage of methane (CH_4) and carbon dioxide (CO_2) present in the biogas was determined.

Wastewater: Chemical Oxygen Demand (COD) and the macronutrients Nitrogen (Total N) and Phosphorus (Total P) were determined for the liquid fraction of the effluent (Table 1).

Statistical Method: Two fixed levels of Organic Load (OL) were evaluated: OL5% and OL15%, over 4 periods of 40 days each, with 10 days of adaptation at each OL level. Sampling was conducted weekly in triplicate, averaging the biogas measurements per week. For the liquid effluent, samples were collected as the stabilization ponds were filled.

The obtained data were analyzed using differential statistics (biogas) and only descriptive statistics (wastewater), with the *R* 4.3.3 software, utilizing the following commands and packages: *fligner.test*, *shapiro.test*, *aggregate*, and *dplyr*. The *P*-value was calculated using a one-way ANOVA when the data came from normal and homogeneous distributions.

RESULTS AND DISCUSSION

Facilities and Organic Loads

The source of the organic waste was determined to be from gestating sows with an average weight of 220 kg, excreting an average of 1.8 kg of solid waste. According to daily manual cleaning, each sow consumed 7 liters of water per day. Chao *et al.* (2012) conducted a study on growing pigs (average weight 60 kg) and determined a water usage of 25.5 L per animal for cleaning and treating waste in pens, concluding that the water consumption is high and increases the cost of waste treatment. In this regard, it is suggested that manual cleaning methods could reduce water usage per animal, and consequently, reduce the organic load entering the biodigester, leading to lower costs for the post-treatment and reuse of this water.

Regarding the Organic Load (OL), various data provided by authors to determine the diluent proportions of manure: water and to establish Hydraulic Retention Times (HRT) have been reported (Cubillos-Sierra *et al.*, 2018), to evaluate the efficiency of organic matter removal in anaerobic biodigesters (Alonso-Estrada *et al.*, 2014). In this study, two Organic Loads were determined: a minimum of 5% (ratio 1:9) and a maximum of 15% (ratio 1:5) from the gestation area, considering a Dry Matter (DM) percentage of 30% in the manure

Table 1. Determination of physical-chemical parameters and nutritional concentration of the liquid effluent from a biodigester.

Parameter	Unit	Method
Environmental Temperature	°C	Climate station
CH_4	%	LANDTEC
CO_2	%	LANDTEC
pH y EC	μ S/cm	Potentiometer
COD	mg/L	HACH 8000
N-Total	mg/L	HACH 10072
F-Total	mg/L	HACH 10127
TSS	ml/L	Sedimentación Imhoff

Where: CH_4=methane; CO_2=carbon dioxide; EC=Electrical Conductivity; COD=Chemical Oxygen Demand; Total-N=Total Nitrogen; Total-P=Total Phosphorus; TSS=Total Settled Solids.

(Riascos-Vallejos *et al.*, 2018). Water was added to achieve the established levels for the study, defining the Hydraulic Retention Time as 30 days. The maximum recommended for optimal biodigester operation is 15% organic load, which makes maintenance intervals longer and ensures that with minimum and maximum OL, the effluent is more accessible to treat and meets the official standards established by NOM-001-SEMARNAT-2021. It is worth mentioning that with this percentage of Organic Load (OL), efficient biogas production and proportional quality parameters of methane relative to other components are ensured.

Byproducts

Biogas

Biogas is considered a primary byproduct, and its quality was determined in percentage terms (Table 2). Based on the OL levels, the quality and ratio of CH_4 and CO_2 were not affected in this study and, according to Sepúlveda *et al.* (2020), both OL levels fall within the acceptable methane range (40-70% CH).

According to the treatments established in this study, an important factor that combines the quality of CH_4 with the secondary treatment of the water to be treated is the Total Settled Solids (TSS) (Figure 2). On one hand, the goal was to produce CH_4, and on the other hand, to achieve the treatment of the wastewater derived from the biodigester in the subsequent lagoons of the lagoon system.

In our case, the percentage of removal from liquid influent to liquid effluent was 66% for OL5% and 41% for OL15%, with a higher removal rate at the lower OL ($p>0.05$). This is because, inside the fermentation chamber, methanogenic bacteria consume more organic matter for their development and growth. These values are consistent with those

Table 2. Percentage of methane and carbon dioxide by organic load level.

Organic Charge level	Gas type	
	CH_4 %	CO_2 %
5%	$59.89^a \pm 2.35$	$35.54^b \pm 2.59$
15%	$60.25^a \pm 6.9$	$34.92^b \pm 6.51$

CH_4=methane; CO_2%=carbon dioxide; SD=standard deviation; Identical letters in each column indicate a p-value >0.05.

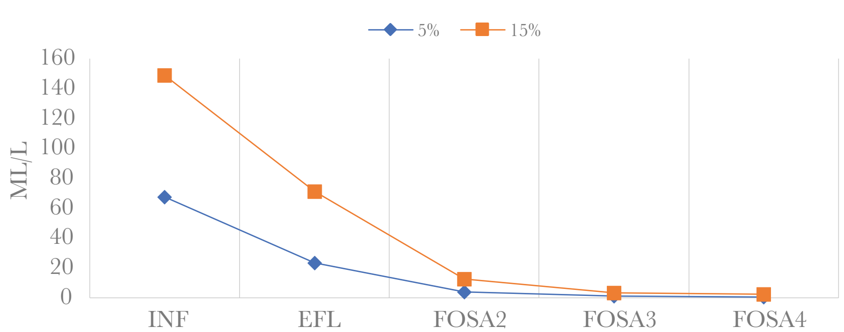

Figure 2. Total Settled Solids by Organic Load Level (5% and 15%).

described by Chibás *et al.* (2017), who reported a 57% removal of Total Settled Solids (TSS) in pig manure samples at the inlet and outlet of biodigesters. Additionally, Trejo-Lizama *et al.* (2014) noted that 50% of the sampled biodigesters in the Yucatán region achieved reference values for organic matter removal. However, they require additional treatments to continue the wastewater treatment process, as was implemented in this study with the addition of three more treatment ponds.

Highlighting the importance of a lagoon system as a complementary treatment, some physical-chemical parameters and macronutrients were determined (Table 4). In both OL levels, the pH value is below neutrality, which is expected because the excretions are acidic in influent (INF). In the case of the effluent (EFL), the pH in the anaerobic fermentation chamber remains in this slightly acidic range. Additionally, the continuous feeding flow of the biodigester carries water from the mixture during internal agitation.

In the subsequent ponds, the pH exceeds neutrality as the Total Settled Solids (TSS) decrease and as Hydraulic Retention Time (HRT) progresses in each pond. These values align with the range (pH 6.0 to 7.8) reported by Cano *et al.* (2016), who worked with liquid pig and cattle effluents over a period of 45 days.

García (2012) defines Electrical Conductivity (EC) as the capacity of water to conduct an electrical current. Pérez González & Mata Varela (2016), working with 6 scale biodigesters fed with pig manure, found an average EC of 3905.3 μ/cm at the outlet of these digesters. In a study of raw and treated wastewater, the average EC was 1763 and 1833 μ/cm, respectively, which is considered high concentration (García-Carrillo *et al.*, 2020). In relation to this study, for both OL levels, the EC in the influent (raw) is similar to the previous study; however, for the effluent (treated), the concentration doubles, as well as in the subsequent ponds. The increase in this parameter from influent to effluent is due to the concentration of dissolved salts in the fermentation chamber, with no consumption of salts by microorganisms despite the organic matter degradation. Furthermore, concentrations rise in the subsequent ponds, exceeding the maximum permissible limits of the (NOM-001-SEMARNAT-2021, which establishes permissible contaminant limits for wastewater discharges into national bodies of water, 2021), which is $<$1000 μ/cm.

Chemical Oxygen Demand (COD) is one of the main parameters for determining water quality. It measures the amount of oxygen required to oxidize the organic matter susceptible to oxidation in a liquid sample and establishes a level of contamination (Rosabal-Carbonell *et al.*, 2012). According to Garzón-Zuñiga & Buelna G. (2014), they measured the performance of an anaerobic digester and two series stabilization lagoons with high concentrations of OL from the farrowing area, with a Hydraulic Retention Time (HRT) $>$60 days, at a farm with 5600 sows. These authors achieved a COD removal of 81.6% at the biodigester outlet. Lansing *et al.* (2008), working with a small-scale biodigester where the excretions came from 12 pigs with an HRT of 44 days, found a COD removal of 87% when measuring the influent and effluent of the biodigester. In this study, by establishing the OL and HRT and measuring the importance of the lagoon treatment train along with the biodigester, we found a removal greater than $>$50% from the influent to the fourth stabilization pond. At the effluent outlet in both OL levels, a higher amount of oxidant is required because the influent, upon contact in the fermentation chamber, contains undegraded organic matter, indicating persistent levels of contamination. As the wastewater progresses through the stabilization ponds, this organic matter decreases. When comparing the two previous studies, it is important to note that the amounts of OL and HRT are different.

Regarding the nutrients present in the liquid effluents subjected to a digestion process (Table 3), Total Nitrogen (TN) and Total Phosphorus (TP) were prominent. In a pig farm, producing an average of 10.2 kg of solid waste, the water used to feed a biodigester originated from the washing process of the pens, at a ratio of 1:4 (manure: water) with an HRT of 43 days. Peñafiel *et al.* (2021) obtained 230±18 *vs.* 373±27 mg/L of TN and 53±5.7 *vs.* 290±21 mg/L of TP, from influent to effluent of the biodigester, respectively. Comparing with this study, it was observed that, very likely due to the similarity of OL and shorter HRT, the two macronutrients increased, indicating that during the anaerobic fermentation process, most of the nutrients in the liquid are retained (Martínez-Hernández & Francesena-López, 2018).

In another study, working with bovine waste, Cabos Sánchez *et al.* (2019) observed that the Total Nitrogen (TN) initially decreased and then increased over time in the liquid effluent measurements. In the case of Total Phosphorus (TP), it decreased over time. The author concluded that these variations depend on the type and amount of Organic Load (OL) used to achieve the concentrations. In this study, Total Nitrogen (TN) was retained as it passed through the ponds, while Total Phosphorus (TP) decreased. According to the

Table 3. Nutrients in influent, liquid effluent, and pig wastewater treatment ponds by Organic Load level.

Simple origin	Organic Charge level			
	5%		15%	
	NT mg/L	FT mg/L	NT mg/L	FT mg/L
INF	128.33±145.9	173.16±184.4	111.90±123.4	130.87±171.7
EFL	436.93±142.1	249.44±210.0	554.62±345.4	309.29±319.6
Fossa 2	348.09±116.8	84.87±52.4	464.36±134.0	103.56±191.5
Fossa 3	267.91±169.4	37.96±24.7	365.25±146.3	40.51±35.1
Fossa 4	217.32±145.86	37.90±24.1	342.49±82.2	17.59±18.2

Where: INF=Influent; EFL=Liquid Effluent; TN=Total Nitrogen; TP=Total Phosphorus; mean ± standard deviation.

Table 4. Physicochemical parameters of influent, liquid effluent and pig wastewater treatment fossas by organic load level.

Sample origin	Organic load level							
	5%				15%			
	TSS ml/L	pH	EC μs/cm	COD mg/L	TSS ml/L	pH	EC μs/cm	COD mg/L
INF	67.45±8.21	6.1±0.17	2225.0±1488.5	738.72±1003.6	81.38±64.62	6.3±0.18	1842.5±757.4	1807.7±3452.8
EFL	23.27±29.06	6.7±0.31	3503.2±1085.9	1444.2±844.2	48.02±76.7	6.6±0.25	4705.2±1247.7	2522.5±2745.6
Fossa 2	3.98±7.44	7.2±0.18	3669.42±514.6	677.0±449.1	8.51±7.87	7.2±0.16	2942.5±927.4	1057.7±484.6
Fossa 3	1.26±1.19	7.4±0.08	2983.3±853.6	600.2±471.7	2.02±1.99	7.4±0.15	3366.7±1258.5	708.3±335.3
Fossa 4	0.51±0.24	7.6±0.16	3228.0±659.9	690.6±348.4	1.89±3.13	7.6±0.11	3546.5±1363.5	409.1±128.9

Where: INF=Influent; EFL=Liquid effluent; TSS=Total Settled Solids, EC=Electrical Conductivity; COD=Chemical Oxygen Demand.

resulting concentrations, the Organic Load (OL) levels should be considered, and the post-treatment with stabilization ponds having Hydraulic Retention Time (HRT) should be included. The filling times of the biodigester should be standardized, and the type of organic matter intended for the fermentation chamber should be established to determine compliance with the maximum permissible limits set by NOM-001-SEMARNAT-2021.

CONCLUSIONS

Based on the obtained results, the physicochemical and nutritional parameters of liquid piggery effluent derived from a biodigester complemented by a lagoon system, it is essential to determine a maximum and minimum Organic Load (OL) to ensure a good percentage of methane. Since the liquid effluents do not comply with the established Official Mexican Standards (NOMs), they continue to be a problem for producers due to lack of training, resources, and environmental awareness. Therefore, the implementation of additional systems to the biodigester for wastewater treatment (known as complementary treatments) is necessary. Biodigesters should be integrated into a waste management system so that their products serve as a basis for implementing another process or system.

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In 2009, the Livestock Production Module was integrated into the Centro-Altos de Jalisco Experimental Field, with a focus on the Sustainable Integral Production System (SIPIS).

REFERENCES

Alonso-Estrada, D., Lorenzo-Acosta, Y., Díaz-Capdesuner, Y. M., Sosa-Cáceres, R., & Angulo-Zamora, Y. (2014). Tratamiento de Residuales Porcinos Para la Producción de Biogás. ICIDCA. *Derivados de La Caña de Azucar, 48*(3), 16-21. http://www.redalyc.org/articulo.oa?id=223132853003

Barrera-Cardoso, E., Odales-Bernal, L., Carabeo-Pérez, A., Alba-Reyes, Y., & Hermida-García, F. (2020). Compilation of theoretical aspects on biogas production technologies at rural scale. *Tecnología Química, 40*(2), 303-321. https://doi.org/http://scielo.sld.cu/pdf/rtq/v40n2/2224-6185-rtq-40-02-303.pdf

Cabos Sánchez, J., Bardales-Vázquez, C. B., León-Torres, C. A., & Gil-Ramírez, L. A. (2019). Evaluación de las concentraciones de Nitrógeno, Fósforo y Potasio del biol y biosol obtenidos a partir de estiércol de ganado vacuno en unbiodigestor de geomembrana de policloruro de vinilo. *Arnaldoa, 26*(3), 1165-1176. https://doi.org/10.22497/arnaldoa.263.26321

Cano-Hernández, M., Bennet-Eaton, A., Silva-Guerrero, E., Robles-González, S., Sainos-Aguirre, U., & Castorena-García, H. (2016). Caracterización de bioles de la fermentación anaerobica de excretas bovinas y porcinas. *Agrociencia*, 50, 471-479. https://doi.org/https://www.scielo.org.mx/scielo.php?pid=S1405-31952016000400471&script=sci_arttext

Chao-Espinosa, R., Sosas-Caceres, R., & Díaz-Capdesuñer, Y. (2012). Gasto de agua de limpieza y tratamiento del residual en naves de ceba porcina. *Mecanización Pecuaria, 21*(3), 69-72. https://www.redalyc.org/articulo.oa?id=93223725012

Chibás-Guevara, O., Casanovas-Cosio, E., & Pérez-Ponce, A. (2017). Comparison of the efficiency of the fixed dome and geo-membrane biodigesters in the swine production systems in the Cienfuegos province. *Revista Científica Agroecosistemas, 5*(1), 79-83. http://aes.ucf.edu.cu/index.php/aes/index

Cubillos-Sierra, D. F., Huertas-Huertas, D. M., & Contreras-León, H. (2018). Evaluación de la Eficiencia de Remoción de Materia Orgánica de un Biodigestor Tubular Anaerobio a Escala Piloto. *Ciencia e Ingeniería, 5*(1), 43-57. http://revistas.uniguajira.edu.co/index.php/cei

Domínguez-Araujo, G., De la Mora-Orozco, C., González-Acuña, I., Galindo-Barboza, A., & Arias-Castellanos, J. (2023). Calidad de subproductos derivados de un biodigestor alimentado con dos cargas orgánicas de residuos porcícolas. *Abanico Veterinario*, 13, 1-13. https://doi.org/10.21929/abavet2023.5

Durante-Mühl, D., & De Oliveira, L. (2022). Features of anaerobic digestion plants in the brazilian agricultural sector. *Cleaner and Circular Bioeconomy*, 1, 100001. https://doi.org/10.1016/j.clcb.2021.100001

Galindo-Barboza, A. J., Domínguez-Araujo, G., Arteaga-Garibay, R. I., & Salazar-Gutiérrez, G. (2020). Mitigation and adaptation to climate change through the implementation of integrated models for the management and use of livestock residues. Review. *Revista Mexicana De Ciencias Pecuarias*, 11, 107-125. https://doi.org/10.22319/RMCP.V11S2.4697

García, Á. (2012). Criterios modernos para evaluación de la calidad del agua para riego.

García-Carrillo, M., Luna-Ortega, J. G., Gallegos-Robles, M. Á., Preciado-Rangel, P., Cervantes-Vázquez, M. G., & González-Salas, U. (2020). Impact of wastewater on soil properties and accumulation of heavy metals. *Terra Latinoamericana, 38*(4), 907-916. https://doi.org/10.28940/terra.v38i4.556

Garzón-Zuñiga, M. A., & Buelna G. (2014). Caracterización de aguas residuales porcinas y su tratamiento por diferentes procesos en México. *Revista. Internacional de Contaminación Ambiental, 30*(1), 65-79. https://doi.org/https://www.scielo.org.mx/pdf/rica/v30n1/v30n1a6.pdf

Kebreab, E., Liedke, A., Caro, D., Deimling, S., Binder, M., & Finkbeiner, M. (2016). Environmental impact of using specialty feed ingredients in swine and poultry production: A life cycle assessment. *Journal of Animal Science, 94*(6), 2664-2681. https://doi.org/10.2527/jas.2015-9036

Lansing, S., Botero R, & Martin JF. (2008). Waste treatment and biogas quality in small-scale agricultural digesters. *Bioresource Technology, 99*(13), 5881-5890. https://doi.org/10.1016/j.biortech.2007.09.090

Magnusson, T., Zanatta H, Larsson M, Kanda W, & Hjelm O. (2022). Circular economy, varieties of capitalism and technology diffusion: Anaerobic digestion in Sweden and Paraná. *Journal of Cleaner Production*, 335. https://doi.org/10.1016/j.jclepro.2021.130300

Martínez-Hernández, C. M., & Francesena-López, Y. (2018). Tratamiento y utilización de efluentes de instalaciones de biogás como abonos orgánicos, revisión y análisis. *Centro Agrícola, 45*(2), 83-92. http://scielo.sld.cu/pdf/cag/v45n2/cag12218.pdf

NOM-001-SEMARNAT-2021, Que Establece Los Límites Permisibles de Contaminantes Las Descargas de Aguas Residuales En Cuerpos Receptores Propiedad de La Nación., Pub. L. No. 001-SEMARNAT-2021 (2021).

Penafiel, A., Collahuaso E, Pérez MA, & Diéguez SK. (2021). Caracterización del Funcionamiento de un Biodigestor Tubular Alimentado con Estiércol Porcino en la Amazonia Ecuatoriana. *Ingenio Magno, 12*(1), 6-24. http://revistas.ustatunja.edu.co/index.php/ingeniomagno/article/view/2306/1961

Pérez-González, Y., & Mata-Varela, M. (2016). Eficiencia del tratamiento de residuales ganaderos en digestores de geomembrana. *Agrosost, 22*(3), 29-36. https://www.redalyc.org/articulo.oa?id=93931761025

Pinos-Rodríguez, J. M., García-López, J. C., Peña-Avelino, L. Y., Rendón-Huerta, J. A., González-González Cecilia, & Tristán-Patiño Flor. (2012). Impactos y regulaciones ambientales del estiércol generado por los sistemas ganaderos de algunos países de América. *Agrociencia, 46*(4), 359-370. https://doi.org/https://www.scielo.org.mx/pdf/agro/v46n4/v46n4a4.pdf

Riascos-Vallejos, A. R., Apráez-Guerrero, J. E., Vargas M, D. P., & Londoño-Arcila, A. (2018). Efecto de la suplementación con ensilaje porcino sobre los indicadores productivos en bovinos Hartón del Valle. *ORINOQUIA*, 22, 34-40.

Rosabal-Carbonell, y, Chang-Huerta, L., Perez-Aballe, N., & Morales-León, J. A. (2012). Evaluación de la demanda química de oxígeno en aguas de la provincia de Granma, Cuba. *Revista Latinoamericana de Recursos Naturales, 8*(1), 15–20.

Sepúlveda-Calderin, I., Hernández-González, J., Sepúlveda-Vargas, R., Tejada-Bustos, H., Espinosa-Corrales, D., & Wilches-Bonilla, C. (2020). Modelo de biodigestores para la producción porcina en la granja La Nueva Gloria. In Alternativas de sostenibilidad ambiental para comunidades en el departamento de Córdoba (Vol. 1, pp. 105-123). Editorial Universidad Pontificia Bolivariana. https://doi.org/10.18566/978-958-764-908-6.

Somagond, A., Vinay B, Khan SS, Wankhade P, Miranda C, & Kanaka K. (2020). Mitigation of Odour in Swine Production Facilities: A Scientific Approach. *International Journal of Livestock Research, 10*(4), 1-12. https://doi.org/10.5455/ijlr.20.

Trejo-Lizama, W., Vázquez-González, L., J Uicab, A., Castillo-Caamal, J., Caamal-Maldonado, A., Belmar-Casso, R., & Santos-Ricalde, R. (2014). Eficiencia de remoción de materia orgánica de aguas residuales porcinas con biodigestores en el Estado de Yucatan, México. *Tropical and Subtropical Agroecosystems, 17*(2), 321-323. http://www.redalyc.org/articulo.oa?id=93931761025.