Revista Ciencias Técnicas Agropecuarias, Vol. 33, No. 2, april-june 2024, E-ISSN: 2071-0054

ORIGINAL ARTICLE

Anaerobic digestion of cow manure in a plug-flow digester: A sustainable approach

Digestión anaerobia de estiércol vacuno en un digestor de flujo pistón: un acercamiento sostenible

https://cu-id.com/2177/v33n2e06

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ABSTRACT: In this study, a pilot-scale plug flow reactor has been operated at a hydraulic retention time of 30 d with substrate concentration of total solids (7-10 %) under room temperature ranging from 25-38 °C with a working volume of 1.44*10^{-3} m^3 during 186 days. The average chemical oxygen demand (COD) removal was 66.9 % operating at 1.7 kg_{VS}/m^3d. Moreover, the alkalinity to total inorganic carbon rated 0.31 being considered a proper value for the operational control of the reactor. In addition, 65.1 % of Total Volatile Solids removal was attained. The specific biogas and methane yields were up to 0.22 m^3/kg VS, 0.25 m^3/kg VS, respectively. Long-term operation in a pilot scale demonstrated the technological potential and industrial application of cattle manure treatment for biogas production as a circular economy contribution.

Keywords: Biodegradability, Circular Economy, Local Development.

RESUMEN: En este estudio, se operó un reactor de flujo pistón a escala piloto con un tiempo de retención hidráulica de 30 días con una concentración de sustrato de sólidos totales (7-10 %) a temperatura ambiente que oscilaba entre 25 y 38 °C, con un volumen de trabajo de 1,44 *10^{-3} m^3 durante 186 días. La remoción promedio de la demanda química de oxígeno (DQO) fue del 66,9 % operando a 1,7 kgVS/m^3d. Por otro lado, la relación de la alcalinidad con respecto al carbono inorgánico total fue de 0,31, considerándose un valor adecuado para el control operativo del reactor. Además, se alcanzó el 65,1 % de remoción de Sólidos Volátiles Totales. Los rendimientos específicos de biogás y metano fueron de hasta 0,22 m^3/kg VS y 0,25 m^3/kg VS, respectivamente. La operación a largo plazo a escala piloto demostró el potencial tecnológico y la aplicación industrial del tratamiento del estiércol de ganado para la producción de biogás como contribución a la economía circular.

Palabras clave: biodegradabilidad, economía circular, desarrollo local.

INTRODUCTION

Anaerobic degradation has proved to be a suitable method of wastes stabilization where valuable by-products are generated. The application nowadays embraces the generation of biogas to support the concept of bioenergy farms (Manilal *et al.*, 2019). On the other hand, low-tech digesters are sustainable technologies to biodegrade liquid agro-wastes and to produces a liquid effluent, which can be reused in agriculture as a biofertilizer (Juanpera *et al.*, 2022). This mature technical concept is applied in contrast to natural degradation of manure which provokes environmental damages and contributes to emissions of methane and carbon dioxide during fermentation supporting the concept of circular economy.

Numerous benefits but also disadvantages have been demonstrated along years of AD practice in Latin America. In terms of technologies at local level, the plug-flow anaerobic reactor (PFAR) is one of the most used. According to ideal flow-models, in this case the mixing of substrate and water along the fermentation moves through the longitudinal section of the reactor, expressing an organic loading rate variation from

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Received: 05/12/2023
Accepted: 13/03/2024

higher to lower values. In comparison to other local techs, the efficiency in chemical oxygen demand (COD) removal is higher and no extra capacity enhancement is required (Gómez *et al.*, 2019).

Nevertheless, the PFAR time-life is shorter than the completely mixing technologies, the use of high-density polyethylene materials to built-in the PFAR have reduced the reactor breakage but still the solid accumulation at the end of the process remains as a non-solved problem. Numerous efforts have been developed to solve this topic focused in promoting the degradation of recalcitrant lignocellulosic components of cow manure (CM) with good results in co-digestion and chemical pretreatments (Li *et al.*, 2021). However, not too much efforts have been directed to the initial separation process at the input. For this reason, the objective of this work is to study the anaerobic treatment of cow manure in a pilot-scale plug flow reactor at variable substrate concentration of total solids provided from different receiving chambers before the reactor input.

MATERIALS AND METHODS

Characterization of raw material

Cattle manure (CM) was used as substrate provided by the Farm association "Santiago", located in Marianao (Havana, Cuba). The CM was homogenized manually with the help of a shovel, and then collocated in three vessels acting as receiving chambers, connected each other through internal cavities. The chambers were designed to manually remove the lower-density solids at the upper level of liquid in each. Only the liquid of the third chamber was allowed to be use as substrate. The CM substrate was refrigerated and replaced every other day. The physic-chemical characteristics monitored by gravimetric method according to (APHA-AWWA-WEF, 2012) Carranzo, (2012) standards for the raw material were total solids content (TS), volatile solids (VS), humidity and ashes. Chemical Oxygen Demand was determined through reflux standard method.

Experimental assay

The continuous anaerobic process was carried out in a pilot-scale plug flow reactor at a hydraulic retention time of 30 d at room temperature ranging from 25-38 °C. The general characteristics of the reactor are:

- Effective volume (mL) 1440
- Gas volume chamber (mL) 260
- Length (cm) 42
- Diameter (cm) 7.62

The reactor has a length/diameter ratio is approximately 1/6. There is not much literature on this subject, however, a ratio of 1/6 to 1/12 is within the range that maximizes the conversion of volatile solids and methane generation (Juanpera *et al.*, 2022). The substrate concentration of total solids varied from 7 to 10 %. The PFAR was operated under room temperature ranging from 25-38 °C during 186 days. Biogas volume was measured by liquid displacement in columns filled with a slightly acid solution. The PFAR scheme is shown in Figure 1.

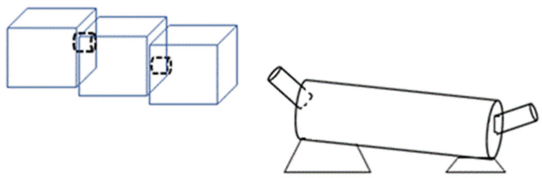

FIGURE 1. Experimental installation of the plug-flow anaerobic reactor.

Start-up of the process

The reactor was inoculated with sieved-pretreated cow manure from the same farm. The starting-up process was developed with a fed-batch procedure during 15 days until reaching the effective volume. During the next 20 days, a degasification process occurred and stable conditions of pH (6.8-7.6) and VFA/TIC (0.18-0.34) were achieved. The anaerobic process was considered started-up when steady-state conditions were reached.

Kinetic Model

The design and optimization of anaerobic digestion processes for biogas production can be improved by

TABLE 1. Description of the method and equipment used for the characterization of physical-chemical parameters

Parameter	Method	Equipment
Hydrogen potential	Potentiometric	Fisher Scientific Accumet AB150
DQO	UV-Vis spectrophotometer	Thermo Scientific - Evolution 60S
ST, SF y SV	Gravimetric	Memmert D-91126
AGV/Alc ratio	Potentiometric/rating	Fisher Scientific Accumet AB150
Composition of biogas	gas meter	Multitec®545

mathematical models developed from mechanistic studies that lead to a deep understanding of very complex transport phenomena, microbial biochemical kinetics and stoichiometric relationships. associated with anaerobic digestion. Anaerobic digesters often present stability problems, which can be avoided only by appropriate control strategies. Such strategies generally require the development of appropriate mathematical models, which adequately reflect the key processes taking place (Shete y Shinkar, 2013).

Kinetic modeling is a generally accepted approach to defining specific system performance parameters. The results of kinetic modeling could additionally be used to estimate the treatment effectiveness and system characteristics of full-scale reactors operating under similar conditions. The success of any biological treatment plant lies in the kinetics of the process, as it determines the dimensions of the unit and dictates the control parameters and operating values.

To quantify the performance of a biological wastewater treatment system, it is necessary to develop relationships to evaluate the effect of operating variables such as volumetric organic loading (VOC) and hydraulic retention time (HRT) on substrate utilization, biomass and the formation of main products or metabolites (Aslanzadeh *et al.*, 2014). Modeling a complex process such as AD requires a good understanding of the factors associated with system performance and process stability. Some of these factors include substrate composition, inhibitory compounds, and microbial growth. Substrate composition influences disintegration/ hydrolysis and methane yield. The biodegradability of the substrate determines the rate of methane production.

Inhibition causes a reduction in the reaction rate of the microorganisms, creating unfavorable conditions in the reactor. Among the main inhibitors are low pH values, the accumulation of VFA, hydrogen and ammonia. Sometimes, the accumulation of intermediate products formed during the AD process can also impede the biological reaction. The way of life of microorganisms in a reactor, whether suspended in the liquid or attached to the substrate, makes a significant difference in the efficiency of AD (Manchala *et al.*, 2017). Biofilm growth systems are more effective in enhancing hydrolysis and synergistic cooperation between AD microbial communities. Therefore, specific models for biofilm-based AD processes have also been established.

Furthermore, the mode of operation of the reactor also plays an important role in the performance of a DA process. Last but not least, the concentration of total solids (ST) in the AD process significantly affects its effectiveness, since at high concentrations of ST, the diffusive processes are limited, contributing to the complexity of the model.

Generally, unstructured kinetic models are the most frequently used to model microbial systems, because they are simple but good enough for technical purposes (Gavala *et al.*, 2003). Of the various kinetic models available in the literature, the Monod model, the second-order Grau model, the modified Stover-Kincannon model, and the first-order model are the most used to determine the kinetics of substrate removal. They are verified by comparing the experimental data with those predicted when the hydraulic retention time is decreased.

In this case the kinetics of the process were approximated using the modified Stover-Kincannon model. This model assumes the substrate removal rate as a function of the substrate loading rate. Although originally the term organic load was referred to the area of the biodisc reactor (original reactor for which the model was proposed), the simple change of area by volume allowed its use to be expanded, resulting in the currently called modified Stover-Kincannon Model. (Sathyamoorthy, 2019).

This model is deployed assuming the variation in the substrate concentration, depending on the organic load applied and eliminated, as shown in equation 1:

$$\frac{dS}{dt} = \frac{Q}{A}(S_O - S_e) \quad (1)$$

where:

dS/dt- substrate removal rate,

So and Se- substrate concentration at the beginning and in the effluent (kg m^{-3}),

Q- volumetric flow of waste (m^3 d^{-1}),

A- cross-sectional area at the passage of the volumetric flow (reactor area) (m^2).

In this way, the removal rate of the substrate dS/dt (kg/m3d) is related to the maximum utilization rate of the substrate (Umax) and the saturation constant (KB), both expressed in kg/m3d, according to the equation 2

$$\frac{dS}{dt} = \frac{U_{máx}(QS_O/A)}{K_B + (QS_O/A)} \quad (2)$$

Substituting QS_O/A for QS_O/V, where V is the effective volume of the reactor, and linearizing the equation, we have

$$\frac{dS}{dt} = \frac{K_B}{U_{máx}} \cdot \frac{V}{QS_O} + \frac{1}{U_{máx}} \quad (3)$$

If the biological process verifies satisfactorily with this model, it can be stated that its behavior follows a microbial dynamic that allows its growth, maintenance and retention under the operating conditions of the RAFP reactor.

RESULTS AND DISCUSSION

Characterization of substrate

The main characteristics for cow manure used in the mixture during the experimentation are shown in Table 2.

TABLE 2. Chemical characterization of the cow manure used in this study

Parameters	CM
TS (%)	22.20
VS on dry basis (%)	62.64
VS/TS	0.62
Ashes (%)	8.39
Moisture (%)	77.80

It can be observed that the TS content of the manure is 22.2% and resembles the results reported by Xu *et al.* (2019); Franqueto *et al.* (2020). In contrast the VS content were 62.4%, which corresponds with other authors Zhao *et al.* (2018); Li *et al.* (2021). The VS values of the studied substrate evidenced the high content of organic matter available to be used in the biological anaerobic digestion process, which is desirable from the economic point of view in relation to methane production.

Operation performance of the anaerobic digestion of cow manure in a plug-flow anaerobic reactor

The biodegradability of the waste was determined from the behavior of the biogas productivity and the COD removal. The results of the PFAR operation is shown in Figure 2.

As explained in Material and Methods, the influent of the process was pretreated in a chamber system in which the substrate was kept until use. The supernatant fibers of the lignocellulosic fraction in cow manure were manually removed and no grating device was used.

In general, the results of CM in the present work are in agreement with those reported in the literature. The COD and VS removal efficiencies varied along the process averaging 66.9 and 65. 1% respectively. The volatile fatty acid (VFA) to total inorganic carbon (TIC) ratio averaged 0.31 and pH values were 7.033 showing that the process was stable (Gómez *et al.*, 2019).

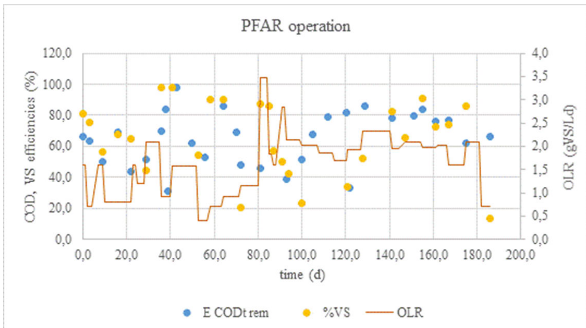

FIGURE 2. Behavior of the cow manure anaerobic process developed in a plug-flow reactor.

The specific biogas and methane yields were up to 0.22 m^3/kg VS, 0.25 m^3/kg VS, respectively (data not shown). The methane yield values were similar to the obtained by the Biomethane potential assessment and are in agreement with those reported Lahboubi *et al.* (2020) in their studies with similar lignocellulosic substrate. However they are lower than those studied by Li *et al.* (2016; 2017) who achieved results in the range of 278 up to 322 NmL CH_4/gVS.

Kinetic assessment

The kinetic assessment was developed using the Stover-Kincannon model as proposed by Sathyamoorthy (2019) and other authors in literature. This model was previously used in high-rate biological reactors as activated sludge and filters. Nevertheless, to fit this model under PFAR operational conditions, can proved that the system is operating similar to the high-rate configurations. The results are graphically exposed in Figure 3.

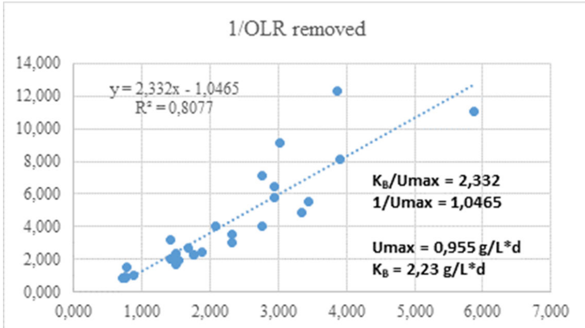

FIGURE 3. Kinetic evolution of the anaerobic process developed in a plug-flow reactor treating cow manure

According to the results represented in Figure 3 the Stover-Kincannon model can be used to approach to the kinetic of the process. Despite the differences between the functioning of the PFAR and those configurations of high-rate performance, the operation of the system allowed to attain adequate results and it can be established that active biomass is properly retained inside the PFAR. To the best of our knowledge, this approximation has been never made for a PFAR configuration.

CONCLUSIONS

The operation of the chamber system was an effective mechanism for low-density solid separation. The plug-flow anaerobic reactor performance to treat cow manure was effective. The average chemical oxygen demand (COD) removal was 66.9 % with 65.1 % of Total Volatile Solids removal operating at 1.7 kgVS/m3d. was attained. The specific biogas and methane yields were up to 0.22 m3/kg VS, 0.25 m3/kg VS, respectively. Long-term operation in a pilot scale demonstrated the technological potential and industrial application of cattle manure treatment for biogas production as a circular economy contribution.

ACKNOWLEDGEMENTS

The authors would like to thank SENACYT, Panama, for financial support

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The authors of this work declare no conflict of interests.
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