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BIOGAS YIELD AND PRODUCTIVENESS OF SWINE MANURE FOR DIFFERENT REACTOR CONFIGURATIONS

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KEYWORDS

Bioenergy, sustainability, swine farms.

ABSTRACT

The progression of the organic loading rate (OLR) up to a certain limit increases biogas production. The limit and operation range vary according to the configuration of the reactor and are associated with other variables that generate different results with respect to biogas yield (BY) and biogas productiveness (BP). The aim of this study was to investigate the effect of the OLR on the BY and BP from swine manure in continuous stirred tank reactors (CSTRs) and upflow anaerobic sludge blanket reactors (UASBs). In the assay with the CSTR, the best operational condition was at an OLR of 0.7 $g_{VS\ add}\ L^{-1}{}_{reactor}\ d^{-1}$ and a hydraulic retention time (HRT) of 18 days. At this operational condition, 0.8 $L_{N\ biogas}\ g_{VS\ add}{}^{-1}$ of BY and 0.6 $L_{N\ biogas}\ L^{-1}{}_{reactor}\ d^{-1}$ of BP were obtained. In the assay with the UASB, the best operational condition was at an OLR of 2.2 $g_{VS\ add}\ L^{-1}{}_{reactor}\ d^{-1}$ and an HRT of two days, and 0.7 $L_{N\ biogas}\ g_{vs\ add}{}^{-1}$ of BY and 1.6 $L_{N\ biogas}\ L^{-1}{}_{reactor}\ d^{-1}$ of BP were obtained. The results demonstrate the effects of OLR changes on the biogas production in the CSTR and UASB, avoiding the underutilization or overloading of such equipment and enabling collaboration in projects for power generation from biogas in swine farms.

INTRODUCTION

Swine production is one of the main livestock activities in the world, particularly in China, Europe, the USA, and Brazil (Tápparo et al., 2019). However, if poorly planned, it can have serious environmental impacts because of the high volume of waste, which is characterized by a high concentration of organic matter, nutrients (phosphorus, nitrogen, and potassium), heavy metals (copper and zinc), pathogens, and antibiotics (Steinmetz et al., 2009; Viancelli et al., 2013).

It is estimated that pork production is responsible for 9% of the total greenhouse gas emissions attributed to the livestock sector. In this amount, 19% comes from the methane produced by inadequate manure management (FAO, 2013; Bilotta et al., 2019).

Anaerobic digestion (AD) is widely used for the treatment of animal waste and to mitigate the environmental impacts of swine production. In addition, the utilization of methane gas as a renewable energy source can have positive economic and environmental impacts (Kumaran et al., 2016; Kunz et al., 2018).

To ensure that AD is effective, it is necessary to control the factors that affect the process, such as pH, temperature, hydraulic retention time (HRT), solid retention time (SRT), carbon-to-nitrogen ratio, and organic loading rate (OLR) (Panigrahi & Dubey, 2019). It is important to understand the operating differences of each reactor configuration; otherwise, underutilization or overloading of the reactor can occur.

Continuous stirred tank reactors (CSTRs), which are used in full-scale biogas plants, and upflow anaerobic sludge blanket reactors (UASBs), which are widely utilized for treating municipal wastewater and livestock effluents, are reactors that clearly reflect these operational differences.

A CSTR is used for substrates with a high level of total solid (TS) composition, such as for substrates with up to 10% TS and an HRT of 15 days. A UASB is employed for substrates with as much as 1% TS and an HRT of 1–3 days (Kunz, et al., 2019; Ali Shah et al., 2014; Van et al.,

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2019; Wu et al., 2019). These differences imply that there are different ranges of OLR for these two types of reactors; hence, they were chosen for this study.

The OLR is an important parameter because it indicates the quantity of organic matter that can be introduced into the digesters daily so that it can be converted to biogas in AD (Alepu et al., 2018).

The purpose of this study was to investigate the effect of the OLR on the BY and BP from swine manure (SM) for CSTRs and UASBs.

MATERIAL AND METHODS

SM sampling

The wastewater samples were collected from an SM treatment system (SMTS) at Embrapa Swine and Poultry, located in Concordia, Santa Catarina, Brazil (Kunz et al., 2009). Samples were collected at different points of the SMTS. The collection points of SM for the reactor feeding are shown in Figure 1, where point A was used to feed the CSTR and point B to feed the UASB. Samples A were stored frozen until use. On the day when the samples were to be used to feed the reactor, they were acclimated to 37 ºC before feeding the reactor. Samples B were stored at 4 °C and acclimated to 20 ºC before feeding the reactor. The samples were replaced every two days.

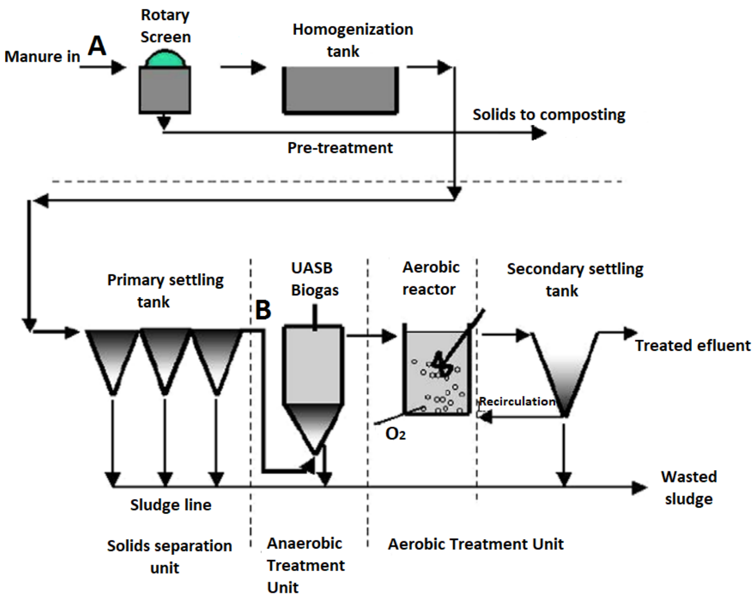

FIGURE 1. Scheme of swine manure treatment system (SMTS): **A)** samples were collected to feed the continuous stirred tank reactor (CSTR) and **B)** samples were collected to feed the upflow anaerobic sludge blanket reactor (UASB) (adapted from Kunz et al., 2009)

Table 1 shows the sample TS and volatile solid (VS) characterization.

TABLE 1. Collected swine manure sample characterization for total solid (TS) and volatile solid (VS) at different points of the SMTS.

Sampling point	(g_{TS} L^{-1})	(g_{VS} L^{-1})	VS/TS ratio
A	29.8±7.5	21.4 ±6.0	0.72
B	10.1±3.6	6.2±2.5	0.61

Inoculum and reactor startup

The CSTR startup was performed using 20% (v.v^{-1}) of inoculum prepared by mixing three equal volumes of samples collected sludge from a UASB treating SM, sludge from a UASB reactor treating gelatin manufactory effluent, and fresh dairy cattle manure (Steinmetz et al., 2016). The UASB startup was performed with 20% (v.v^{-1}) of the inoculum obtained from a UASB that treats effluents from a gelatin manufactory. All reactors were filled to the working volume with 80% (v.v^{-1}) of tap water and fed with the respective swine samples that were collected, as shown in Figure 1.

Experimental design for CSTR

The reactor was manufactured using polyvinyl chloride (PVC) concentric pipes, with diameters of 200 mm (internal) and 250 mm (external), a total capacity of 20 L, and a working volume of 17 L. The CSTR was operated at 37 °C ± 1 °C (external thermostatic water bath: MB-5, Julabo) and substrate continuous stirring adjusted at 70 rpm (RW 20 digital, IKA) and was fed semicontinuously with SM daily.

The laboratory assays were divided into three phases (Table 2). In phase I, an OLR of 1.0 $g_{VS\ add}$ $L^{-1}{}_{reactor}$ d^{-1} was applied. In phase II, the OLR progression began with 2.0 $g_{VS\ add}$ $L^{-1}{}_{reactor}$ d^{-1} and increased to 3 $g_{VS\ add}$ $L^{-1}{}_{reactor}$ d^{-1}. In phase III, the OLR was adjusted using the HRT to avoid the washout that occurred in the previous phase owing to the composition of the VS in the samples, thereby limiting the progression of the OLR.

TABLE 2. Experimental phase organic loading rates (OLRs), volatile solid (VS) composition, and hydraulic retention time (HRT) applied for the assays with continuous stirred tank reactor (CSTR).

OLR ($g_{VS\ add}$ L^{-1} $_{reactor}$ d^{-1})	(g_{VS} L^{-1})	HRT (d)
	Phase I	
1.0	15.0	15
1.0	19.0	19
1.0	20.0	20
1.0	23.6	24
	Phase II	
2.0	21.5	11
3.0	26.0	9
	Phase III	
1.0	18.3	18
1.9	15.0	15
0.7	13.0	18

Experimental design for UASB

The UASB was assembled using acrylic concentric pipes, with diameters of 94 mm (internal) and 250 mm (external), a total capacity of 7.0 L, and a working volume of 6.6 L. The reactor was operated at 37 °C ± 1 °C (external thermostatic water bath: MB-5, Julabo), and it was continuously fed using a peristaltic pump (Milan, BP 600).

The experiments were divided into two phases (Table 3). In phase I, the OLR was controlled through effluent dilution. In phase II, the OLR was controlled through dilution progressive reduction, without changing the HRT (75 h). After that period, the OLR was controlled through flow rate increase and consequent HRT reduction.

TABLE 3. Experimental phase organic load rates (OLRs), volatile solid (VS) composition, hydraulic retention time (HRT), and dilution ratio of swine manure (SM) with water (W) applied for the assays with the upflow anaerobic sludge blanket reactor (UASB).

OLR ($g_{VS\ add.}$ L^{-1} $_{reactor}$ d^{-1})	(g_{VS} L^{-1})	HRT (hours)	Ratio W:SM
	Phase I		
1.5	1.4	22	75:25
2.0	1.9	22	75:25
2.5	2.3	22	70:30
3.0	2.3	18	70:30
	Phase II		
0.5	1.7	75	60:40
0.7	2.3	75	40:60
0.9	2.7	75	20:80
1.4	4.3	75	0:100
1.6	4.3	66	0:100
2.2	4.3	48	0:100
2.9	4.3	36	0:100
8.4	8.4	24	0:100

In many studies on the production of biogas from SM in a UASB reactor, the strategy used for OLR control is effluent dilution (Ramires et al., 2014). The planning used in phase II of the present study made it possible to observe an important change in the characteristic of the sludge blanket, from a granular to a flocculent characteristic.

Analytical methods

The samples were dried at 105 °C for the determination of TS and calcined at 550 °C for VS determination (APHA, 2012). Volatile fatty acids (VFAs), total alkalinity (TA), and the VFA/TA ratio were determined through titration with 0.05 mol L^{-1} of sulfuric acid, from the original pH value to 5.0 VFA/FA and a pH value of 4.4 (Lili et al., 2011). The pH was potentiometrically measured (Hanna, HI 98183). The determination of the total ammonia nitrogen (TAN) was conducted using a flow injection analysis system (FIAlab 2500). Free ammonium (FA) was calculated as follows (Anthonisen et al, 1976):

$$\text{FA}\ (\text{mg L}^{-1}) = \frac{17}{14} \times \frac{[\text{total ammonia as nitrogen}] \times 10^{\text{pH}}}{e^{[6344/(273+T(°C))]} + 10^{\text{pH}}} \qquad (1)$$

The readings of biogas production in the CSTR and UASB were taken using volumetric meters of gas (TGO 5/5, Ritter). The biogas was collected using gas-tight bag samplers (plastic/aluminum foil, Hermann Nawrot AG), and the methane content was analyzed using a portable infrared analyzer (Biogas 5000, Landtec). The biogas volume was then normalized to the standard temperature and pressure, i.e., 0 ºC and 1013 hPa, respectively (Steinmetz et al., 2016).

RESULTS AND DISCUSSION

BY and BP in the CSTR

In the first 15 days of operation an increasing tendency of BP and BY was observed, reaching stability after 40 days of operation (Figures 2a and 2b), making the progression of OLR to phase II possible. In phase II, a decrease in BP and BY was observed, possibly because of the removal of the methanogenic microorganisms of the reactor (washout), caused by the progression of the OLR and decrease in the HRT, from 11 to 9 days in the OLR 2.0 and 3.0 $g_{VS\ add}$ L^{-1} $_{reactor}$ d^{-1}, respectively.

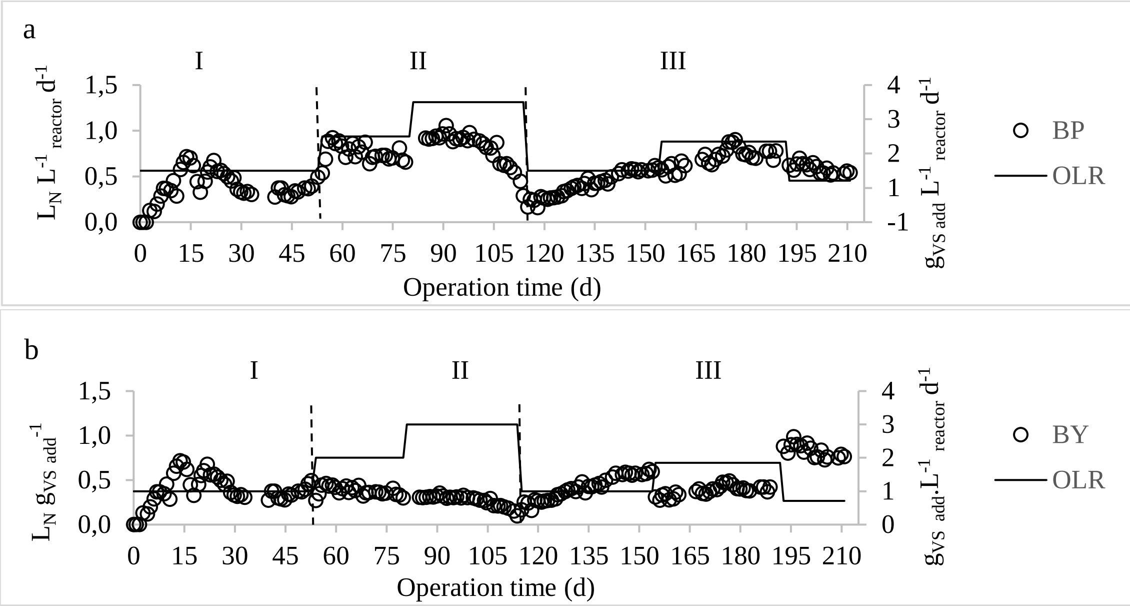

FIGURE 2. (a) Biogas productiveness (BP) and (b) biogas yield (BY) in the continuous stirred tank reactor (CSTR) at different organic loading rates (OLRs): I, II, and III represent the different operational phases

In phase III, the OLR was controlled by the HRT because of the hypothesis that biomass washout caused the progression of OLR and the low solid composition in the substrate. The new experimental design resulted in an OLR of 1.0, 1.9, and 0.7 $g_{VS\ add}\ L^{-1}{}_{reactor}\ d^{-1}$ and an HRT of 18, 15, and 18 days. The increase in the HRT recovered the BP and BY, reinforcing the hypothesis that biomass washout was caused by a low HRT.

The time of the regeneration of methanogenic microorganisms is between 5 and 16 days for *Methanosarcina barkeri* and 10 days for *Methanococcus* (Deublein & Steinhauser, 2011). This became evident because of the CSTR characteristics. It does not have a biomass retention system with a consequent HRT similar to the SRT (Mes et al., 2003).

At a low HRT, more microorganisms are removed with the digestate than generated inside the reactor. This results in a decrease in BY (Seadi, et al., 2008).

Table 4 shows that it is possible to observe, using the coefficient of variation, the instability of the BP and BY in phase II and the beginning of phase III. After 50 days of operation in phase III with OLRs of 1.9 and 0.7 $g_{VS\ add}\ L^{-1}{}_{reactor}\ d^{-1}$, the BP and BY were more stable, possibly because of the adjustment of the HRT favoring the growth of methanogenic microorganisms, avoiding washout. The CSTR was operated with an HRT of 20 days or more to avoid the washout of methanogenic microorganisms (Ali Shah et al., 2014).

TABLE 4. Methane content (CH_4), coefficient of variation (CV), minimum and maximum values for biogas productiveness (BP), and biogas yield (BY) observed in the assays with the continuous stirred tank reactor (CSTR) at different organic loading rates (OLRs).

OLR	HRT (d)	BP Min. – Max.	BY Min. – Max.	CH_4 (%)	CV (%) BP – BY
			Phase I		
1.0	15	0.1 – 0.4	0.1 – 0.4	39 ± 1.7	55.1
1.0	19	0.3 – 0.7	0.3 – 0.7	44 ± 2.2	19.3
1.0	20	0.3 – 0.6	0.3 – 0.6	49 ± 2.9	14.1
1.0	24	0.2 – 0.5	0.2 – 0.5	47 ± 4.4	16.2
			Phase II		
2.0	11	0.2 – 0.9	0.3 – 0.5	52. ± 4	20.4 – 12.3
3.0	9	0.3 – 1.1	0.1 – 0.3	48 ± 5.7	25.5 – 20.8
			Phase III		
1.0	18	0.2 – 0.6	0.2 – 0.6	49 ± 8.8	32.7
1.9	15	0.5 – 0.9	0.3 – 0.5	52 ± 9.7	14.1 – 16.2
0.7	18	0.5 – 0.7	0.7 – 1.0	53 ± 2.5	9.3 – 8.3

Units measurement: OLR ($g_{VS\ add}\ L^{-1}{}_{reactor}\ d^{-1}$); BP ($g_{VS\ add}\ L^{-1}{}_{reactor}\ d^{-1}$); BY ($L_{N\ biogas}\ g_{VS\ add}{}^{-1}$).

Corroborating the washout hypothesis, the beginning of an imbalance of the VFA/TA ratio was observed in phase II (Figure 3); this was, on average, 0.4 ± 0.1 mg HAc mg CaCO3^{-1} with peaks of 0.6 mg HAc mg $CaCO_3^{-1}$.

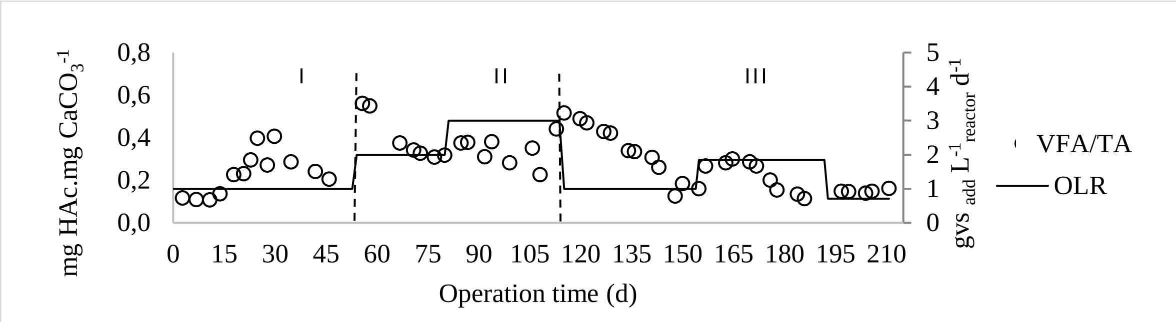

FIGURE 3. Behavior of the volatile fatty acid/ total alkalinity (VFA/TA) ratio in the continuous stirred tank reactor (CSTR) at different organic loading rates (OLRs): I, II, and III represent different operational phases

The VFA/TA parameter is the ratio between the organic acid and the alkaline buffer capacity, and it is commonly used for monitoring and supplying information on the biochemical reactions of AD processes. It has been reported that the VFA/TA ratio should be in the range of 0.3–0.4, and a ratio of more than 0.4 could result in a decrease in biogas production (Veluchamy et al., 2019).

The decrease in biogas production is caused by the imbalance between acidogenesis and methanogenesis, resulting in acidification of the substrate caused by the accumulation of organic acids, thereby making the environment toxic for methanogenic microorganisms (Lili et al., 2011).

The acidogenic bacteria and the methanogenic archaea have different regeneration times, which are approximately 24–36 h and 15 days, respectively (Ali Shah et al., 2014). For this reason, the washout can influence the VFA/TA ratio, that is, there is an imbalance between the production of VFAs and their consumption for the biogas production.

However, that did not cause acidification of the substrate, because the pH value was between 6.9 and 8.0 during the experiment, which is inside the acceptable range for biogas production (Lee et al., 2009).

The principal reason for the changes in pH value was that different batches of samples were used. A pH value of less than 6.2 strongly inhibits the growth of acetoclastic methanogenesis, and when the pH is more than 7.4, these microorganisms can be inhibited using FA. This is because the pH affects the FA concentration, thereby influencing the chemical equilibrium between ammonium and ammonia (Siegrist et al., 2002; Kunz & Mukhtar, 2016).

High concentrations of FA can inhibit the growth of methanogenic archaea because this chemical species crosses the cell membrane, causing potassium ion (K^+) depletion (Kunz et al., 2019; Yang et al., 2018; Kunz et al., 2009; Czatzkowska et al., 2020). The FA increased by approximately 163% in phase II (Figure 4), during the progression of the OLR from 2.0 to 3.0 $g_{VS\ add}\ L^{-1}{}_{reactor}\ d^{-1}$, averaging 88.6 ± 16.9 and 233.2 ± 169.5, respectively.

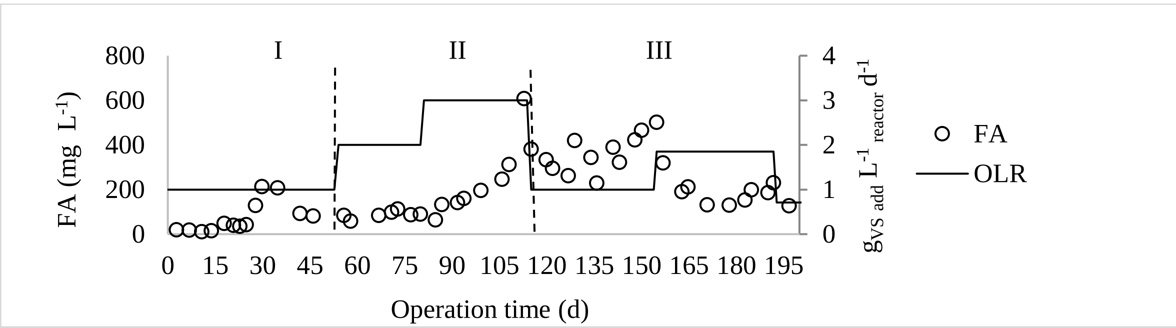

FIGURE 4. Behavior of the free ammonia (FA) in the continuous stirred tank reactor (CSTR) at different organic loading rates (OLRs): I, II, and III represent different operational phases

Braun et al. (1981) observed a decrease in BP in a CSTR treating SM at mesophilic conditions to an FA concentration of 316 mg L^{-1}.

Guo et al. (2013) evaluated the methane (CH_4) production of a CSTR treating SM at three temperatures and an increasing OLR, and they observed the inhibition of production at an FA concentration between 120 and 190 mg L^{-1}.

However, although the FA concentration remained high at the start of phase III, possibly because of the disturbances in the previous phase, the BP and BY were not affected. This may have been because natural selection made the methanogenic microorganisms more resistant to the toxicity of this inhibitor. *Methanosarcina* can use the acetoclastic and the hydrogenotrophic methanogenesis pathways, making them more tolerant to specific inhibitors, such as TAN. They can tolerate levels of as much as 7000 mg TAN L^{-1} (Ali Shah et al., 2014), approximately an FA concentration of 400 mg L^{-1}, calculated using [eq. (1)] and considering pH 7.8 and 37 °C operational conditions during phase III.

BY and BP in the UASB

In phase I, the progression of the OLR from 1.5 to 2.0 $g_{VS\ add}\ L^{-1}{}_{reactor}\ d^{-1}$ increased the BP to 125%. When it was increased to 2.5 $g_{VS\ add}\ L^{-1}{}_{reactor}\ d^{-1}$, the BP exhibited a new increment of 33%. No increment of the BP was observed when the OLR was increased to 3.0 $g_{VS\ add}\ L^{-1}{}_{reactor}\ d^{-1}$. The BY increased to 66% owing to the progression of OLR from 1.5 to 2.0 $g_{VS\ add}\ L^{-1}{}_{reactor}\ d^{-1}$, and then it remained stable at approximately 0.5 $L_N\ g_{VS\ add}{}^{-1}$ (Figures 5a and 5b).

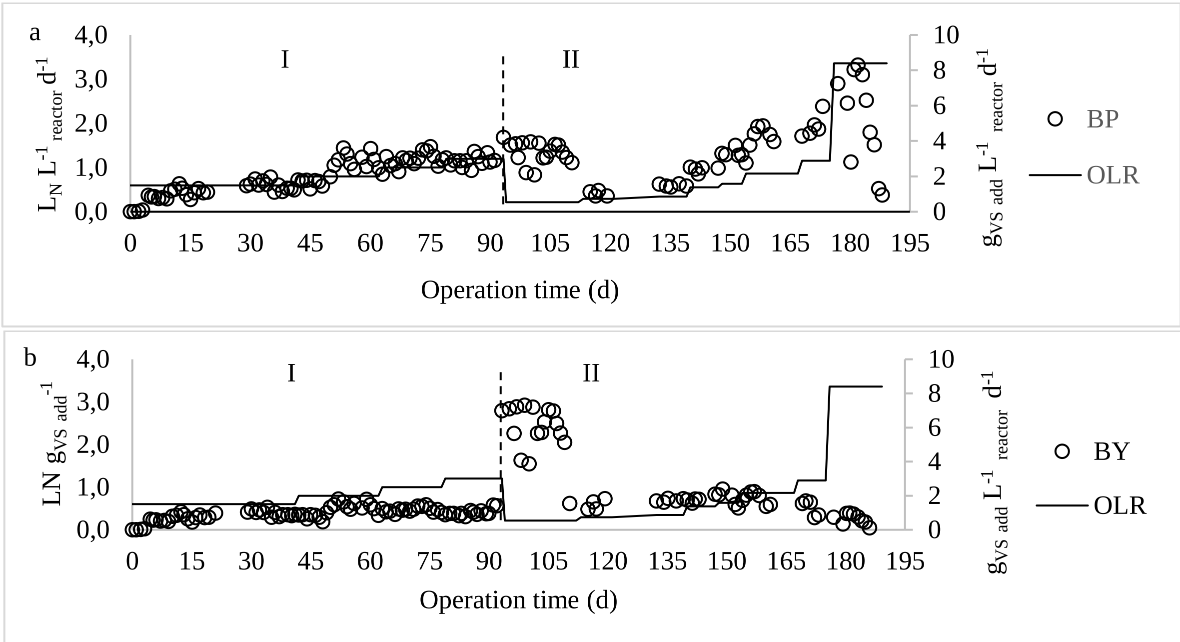

FIGURE 5. (a) Biogas productiveness (BP) and (b) biogas yield (BY) in the upflow anaerobic sludge blanket reactor (UASB) at different organic loading rates (OLRs): I and II represent different operational phases

At the beginning of phase II, with an OLR of 0.5 $g_{VS\ add}\ L^{-1}{}_{reactor}\ d^{-1}$, an increment of BY was observed, as it increased from 0.5 to 2.5 $L_{N\ biogas}\ g_{VS\ add}{}^{-1}$ (Table 5).

TABLE 5. Mean values of biogas productiveness (BP) and biogas yield (BY) in the assay with upflow anaerobic sludge blanket reactor (UASB) at different organic loading rates (OLRs).

OLR	BP	BY	CH_4 (%)	*Dilution W:SM	HRT (hours)
			Phase I		
1.5	0.4 ± 0.2	0.3 ± 0.1	74 ± 2.6	75:25	22
2.0	0.9 ± 0.3	0.5 ± 0.2	74 ± 3.4	75:25	22
2.5	1.2 ± 0.2	0.5 ± 0.1	75 ± 2.7	70:30	22
3.0	1.2 ± 0.2	0.4 ± 0.1	75 ± 2.2	70:30	18
			Phase II		
0.5	1.3 ± 0.2	2.5 ± 0.4	68 ± 8.3	60:40	75
0.7	0.4 ± 0.1	0.6 ± 0.1	69 ± 4.1	40:60	75
0.9	1.0 ± 0.2	1.1 ± 0.3	69 ± 4.7	20:80	75
1.4	0.9 ± 0.1	0.6 ± 0.1	71 ± 3.9	0:100	75
1.6	1.3 ± 0.1	0.9 ± 0.1	73 ± 2.0	0:100	66
2.2	1.6 ± 0.3	0.7 ± 0.1	73 ± 2.0	0:100	48
2.9	1.6 ± 0.5	0.5 ± 0.2	75	0:100	36
8.4	1.9 ± 1.1	0.2 ± 0.1	68 ± 6.5	0:100	24

Water (W); Swine manure (SM); Units of measurement: OLR ($g_{VS\ add}\ L^{-1}{}_{reactor}\ d^{-1}$); BP ($g_{VS\ add}\ L^{-1}{}_{reactor}\ d^{-1}$); BY ($L_{N\ biogas}\ g_{VS\ add}{}^{-1}$).

With an OLR of 2.9 $g_{VS\ add}\ L^{-1}{}_{reactor}\ d^{-1}$, only a sample of the biogas was collected. An increment of BY started in phase II, probably because of the increase in HRT from 18 to 75 h, which increases the contact time between the substrate and biomass.

In phase II, when the OLR was controlled through the reduction of the HRT, without the dilution of the substrate and with 100% SM, the characteristics of the sludge bed began to change, becoming more flocculent. This change limited the process.

When an OLR of 8.4 $g_{VS\ add}\ L^{-1}{}_{reactor}\ d^{-1}$ and an HRT of 24 h were applied, biomass flotation and scum formation were observed, resulting in an abrupt drop in the BP and BY (Figures 5a and 5b). Increasing the OLR caused an increment in the BY, but the equilibrium of the AD process might be disturbed (Mao et al., 2015).

The main reason for biomass flotation was the change in the characteristics of the sludge. As dilution with water was reduced, in phase II, the sludge became more flocculent and less dense. In addition, the ascending hydraulic flow increased from 1.3 cm h^{-1} at the beginning of phase II up to 4.0 cm h^{-1}. At the end this phase, the OLR was 8.4 g_{VS} $L^{-1}{}_{reactor}$ d^{-1}, caused by the reduction of the HRT from 75 to 24 h.

The success of AD and biogas production in the UASB resulted in the establishment of a dense sludge at the bottom of the reactor, where bioconversion of the organic matter into biogas occurs (Seghezzo et al., 1998).

The progression of the OLR affected the FA concentration (Figure 6), and this possibly caused a process of natural selection of the more-resistant microorganisms, although it was not, in principle, the reason for the stoppage of biogas production.

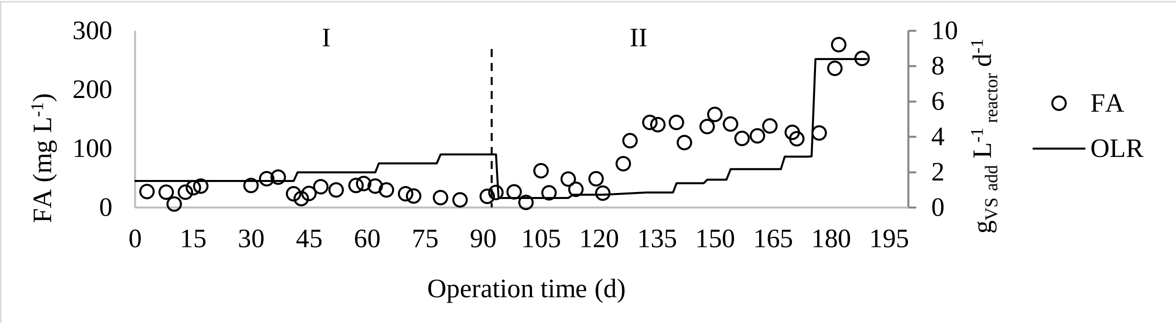

FIGURE 6. Behavior of free ammonia (FA) concentration in the assay with the upflow anaerobic sludge blanket reactor (UASB) at different organic loading rate (OLRs): I and II represent different operational phases

Song et al. (2010) and Silva et al. (2015) studied the dynamics of the population of methanogenic microorganisms and its effects during SM AD in a UASB. The results revealed a predominance of hydrogenotrophic archaea, with *Methanobacteriales* being the largest group. The authors attributed this predominance to the fact that acetoclastic archaea are more sensitive than hydrogenotrophic archaea to pH oscillations and FA concentrations.

The VFA/TA ratio was between 0.1 and 0.2 mg HAc mg $CaCO_3{}^{-1}$ during all experiments (Figure 7), indicating a low biomass input (Lili et al., 2011). Therefore, it can be inferred that biomass flotation was the main reason for the stoppage of biogas production.

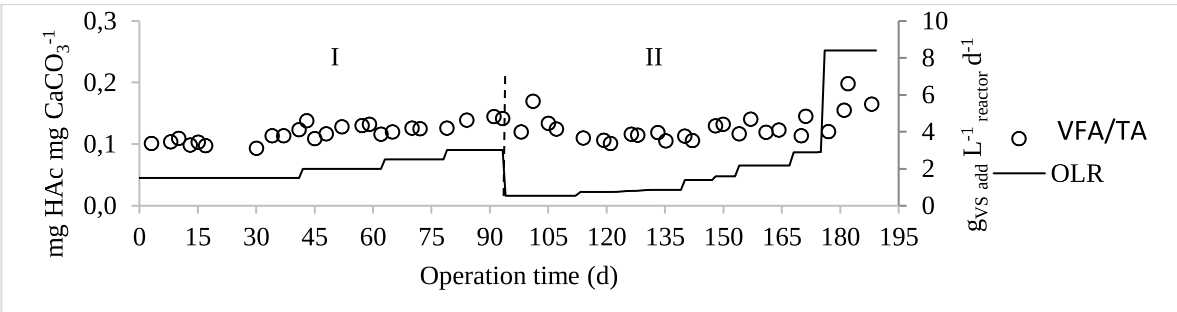

FIGURE 7. Behavior of volatile fatty acid/total alkalinity (VFA/TA) ratio in the assays with the upflow anaerobic sludge blanket reactor (UASB) at different organic loading rates (OLRs): I and II represent different operational phases

The previous treatment of the SMTS (Figure 1) removed coarse solids, leaving the supernatant fraction that contained more biodegradable organic matter.

The production of biogas from the separation of the solid–liquid fraction of SM at different stages of production was studied by Amaral et al. (2016). They observed that the supernatant fraction obtained the highest BY, with values between 0.4 and 1.2 $L_{N\ biogas}$ $g_{VS\ add}{}^{-1}$ and a methane content between 50% and 65%.

The UASB was designed to treat effluents with a low concentration of TS; otherwise, the accumulation of fixed solids could start, formed by nonbiodegradable materials, resulting in the loss of the useful volume of the reactor (Bortoli et al., 2009).

Comparison of biogas production in the CSTR and UASB

Table 6 shows the best results obtained in the present study compared with the results in the related literature for biogas production using SM in CSTRs and UASBs. It is important to observe the operational differences of each reactor configuration, such as the HRT, applied OLR, and TS composition in the substrate.

TABLE 6. Biogas productiveness (BP) and biogas yield (BY) for swine manure (SM) in the continuous stirred tank reactor (CSTR) and upflow anaerobic sludge blanket reactor (UASB) obtained at different operating conditions and the results of other studies on biogas production.

Paper	OLR	TS %	VS %	HRT (d)	BP	BY	CH_4 %
CSTR REACTOR							
Present study	0.7	1.8	1.3	18	0.6	0.8	53
Duan et al., (2019)	1.9	5.0	4.2	22	1.1	0.6	72
Sun et al., (2019)	3.0	9.1	4.5	28	1.2	-	64
Kafle et al., (2012)	1.1	5.2	3.6	32	0.5	0.5	72
UASB REACTOR							
Present study	2.2	0.8	0.4	2.0	1.6	0.7	73
Pacco et al., (2018)	-	-	-	≈ 3.0	0.9	-	≈ 75
Bergland et al., (2015)	≈3.6	1.4	0.7	1.8	-	-	-
Bortoli et al., (2009)	2.8	0.4	0.3	1.0	1.4	1.6	75

Units of measurement: OLR ($g_{VS\ add}$ $L^{-1}{}_{reactor}$ d^{-1}); BP ($L_{N\ biogas}$ $L^{-1}{}_{reactor}$ d^{-1}); BY ($L_{N\ biogas}$ $g_{VS\ add}{}^{-1}$).

The best results of this study were selected based on the stability of production, higher methane content, and higher BP and BY. In the assay with the CSTR, the best operational condition was at an OLR of 0.7 $g_{VS\ add}$ $L^{-1}{}_{reactor}$ d^{-1} and 18-day HRT, with 0.8 $L_{N\ biogas}$ $g_{VS\ add}{}^{-1}$ BY and 0.6 $L_{N\ biogas}$ $L^{-1}{}_{reactor}$ d^{-1} of BP and 53% methane content.

In the assay with the UASB, the best operational condition was at OLR 2.2 $g_{VS\ add}$ $L^{-1}{}_{reactor}$ d^{-1} and two days of HRT, with 0.7 $L_{N\ biogas}$ $g_{vs\ add}{}^{-1}$ of BY and 1.6 $L_{N\ biogas}$ $L^{-1}{}_{reactor}$ d^{-1} of BP and 73% of methane content.

The higher BP and higher methane content observed in the assay with the UASB reactor (Table 5) compared with the values observed under the best conditions with the CSTR reactor (Table 4) resulted from the type of effluent that this reactor configuration was fed. The supernatant fraction of SM contains the highest fraction of biodegradable carbon that is being converted more quickly into biogas (Rico et al., 2012).

This rapid conversion of the substrate to biogas associated with biomass retention (sludge bed) justifies the low HRT in the UASB treating SM; this was, on average, two days of HRT (Table 6). In this reactor configuration, the SRT is longer than the HRT, unlike for the CSTR, where the SRT and HRT are similar. Therefore, an HRT of at least 15 days is indicated in this reactor configuration, considering the time of regeneration of methanogenic microorganisms, between 5 and 16 days (Deublin & Steinhauser, 2011; Kunz, et al., 2019; Mes et al., 2003).

CONCLUSIONS

The results demonstrate the effect of different OLRs on biogas production, the behavior of other variables (HRT, VFA/TA ratio, and FA) in the CSTR and UASB, and important operational information to be applied at full scale to ensure stable biogas production from SM.

The biogas production in the CSTR was limited by the impossible progression of the OLR because of the low TS composition in the samples of SM, approximately 3%, in this reactor configuration. It is possible to treat substrates with as much as 10% TS and to apply a higher OLR without any biomass washout taking place and with better utilization of reactor capacity for biogas production. For this reason, it is the reactor model indicated for anaerobic co-digestion and widely used in biogas plants.

The higher biogas production and the low HRT were the main advantages of the UASB compared with the CSTR. However, application using SM as a substrate is conditioned tO a previous solid removal process, which might increase the costs of biogas production.

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