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Research article

Influence of solid–liquid separation strategy on biogas yield from a stratified swine production system

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ABSTRACT

As the fourth largest swine producer and exporter, Brazil has increased its participation in the global swine production market. Generally, these units concentrate a large number of animals and generate effluents that must be correctly managed to prevent environmental impacts, being anaerobic digestion is an interesting alternative for treating these effluents. The low-volatile solid concentration in the manure suggests the need for solid–liquid separation as a tool to improve the biogas generation capacity. This study aimed to determine the influence of simplified and inexpensive solid–liquid separation strategies (screening and settling) and the different manures produced during each swine production phase (gestating and farrowing sow houses, nursery houses and finishing houses) on biogas and methane yield. We collected samples in two gestating sow houses (GSH-a and GSH-b), two farrowing sow houses (FSH-a and FSH-b), a nursery house (NH) and a finishing house (FH). Biochemical methane potential (BMP) tests were performed according to international standard procedures. The settled sludge fraction comprised 20–30% of the raw manure volume, which comprises 40–60% of the total methane yield. The methane potential of the settled sludge fraction was approximately two times higher than the methane potential of the supernatant fraction. The biogas yield differed among the raw manures from different swine production phases (GSH-a 326.4 and GSH-b 577.1; FSH-a 860.1 and FSH-b 479.2; NH -970.2; FH 474.5 $NmL_{biogas}.gVS^{-1}$). The differences were relative to the production phase (feed type and feeding techniques) and the management of the effluent inside the facilities (water management). Brazilian swine production has increased his participation in the global market, been the fourth producer and the fourth exporter. The segregation of swine production in multiple sites has increased its importance, due to the possibilities to have more specialized units. Generally, these units concentrate a large number of animals and generate effluents that must be correctly managed to avoid environmental impact. Due to the biodegradability of manure, anaerobic digestion is an interesting alternative to treat these effluents. The low volatile solid concentration in the swine manure suggests the need for solid–liquid separation as a tool to improve biogas generation capacity. The present study aimed to determine the influence of simplified and cheap solid–liquid separation strategies (based on screening and settling) and different manure of each swine production phases (gestating and farrowing sows houses, nursery houses and finishing houses) on biogas and methane yield. We collected samples in two gestating sows house (GSH-a and GSH-b), two farrowing sows house (FSH-a and FSH-b), a nursery house (NH) and a finishing house (FH). The Biochemical Methane Production (BMP) tests were performed according to international standard procedure (VDI 4630). The settled sludge fraction responds for 20–30% of raw manure volume, producing 40–60% of the total methane yield. The methane potential of settled sludge fraction was about 2 times higher than the supernatant fraction. There are differences on biogas yield between the raw manure of different swine production phases (GSH-a 326.4 and GSH-b 577.1; FSH-a 860.1 and FSH-b 479.2; NH 970.2; FH 474.5 $NmL_{biogas}.gVS^{-1}$). The differences are relative to production phase

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(feed type, feeding techniques, etc.), but also the management of the effluent inside the facilities (water management).

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1. Introduction

A typical swine production system can be separated into four phases: 1) breeding and gestation (breeding females and their maintenance during the gestation period – 114 days); 2) farrowing (birth of baby pigs until weaning at approximately 7 kg–21–28 days); 3) nursery (care of pigs immediately after weaning until approximately 25 kg–35–42 days); and 4) finishing (feeding pigs from 25 kg to a slaughter weight of 120 kg–90–105 days). The production process is organized according to the market demand and regional characteristics (Dias et al., 2011). The segregation of swine production into multiple sites is increasingly important because it enables more specialized units. Farrow-to-wean, farrow-to-feeder, off-site nursery, feeder-to-finishing and wean-to-finish are the most noteworthy types of units (Miele and Miranda, 2013). The relation between the stratified units and the swine production stages is shown in Fig. 1.

Swine manure characteristics are a function of several factors, such as swine age, diet (feeding and antibiotic) and house design (Brooks et al., 2014). The variability in the methane potential of effluent streams can be associated with changes in production management practices, such as feed, feeding techniques and effluent handling methods (Amaral et al., 2014; Gopalan et al., 2013).

In Brazil, swine waste management strategies primarily include storage in reception pits and land applications (Kunz et al., 2009-a). Anaerobic digestion has intensified in recent years due to the low cost and easy operation of geomembrane-covered lagoons. However, these biodigesters have limitations due to their low technology and low organic loading rate (approximately 0.5 kgVS m^{-3} d^{-1}), high hydraulic retention time (>30 days), low total solid concentration (<3% $w.v^{-1}$) and low biogas yield (0.36 $m^3.kgVS^{-1}.d^{-1}$) (Bortoli et al., 2009; Vivan et al., 2010).

Biogas generation can be improved by the use of better biodigestion technologies; increasing the substrate solid concentration, for example, through co-digestion (Fierro et al., 2014; Zhang et al., 2015); or using preliminary solid–liquid separation processes, such as mechanical separators or screens (Deng et al., 2012; Hjorth et al., 2010; Sutaryo et al., 2013). The total solids content of typical swine manure ranges from 1 to 2% ($w.v^{-1}$) (Deng et al., 2012). Wastewater with a low concentration of organic matter may present low biogas yields, which should be compensated with larger digester reactor and hydraulic retention times (Hamelin et al., 2011).

Manure solid separation or concentration, which is a strategy that can potentially contribute to environmental and biogas/methane yield, has recently increased (Popovic and Jensen, 2012). The best performance strategies have been applied using commercial technologies, such as a) screw presses, b) flocculation using polymers and drainage with filter bland separators, and c) decanter centrifuges (Sommer et al., 2015). These technologies require substantial investment, which may be economically prohibitive for some production scales.

Gravity settling is an attractive option for separation due to its

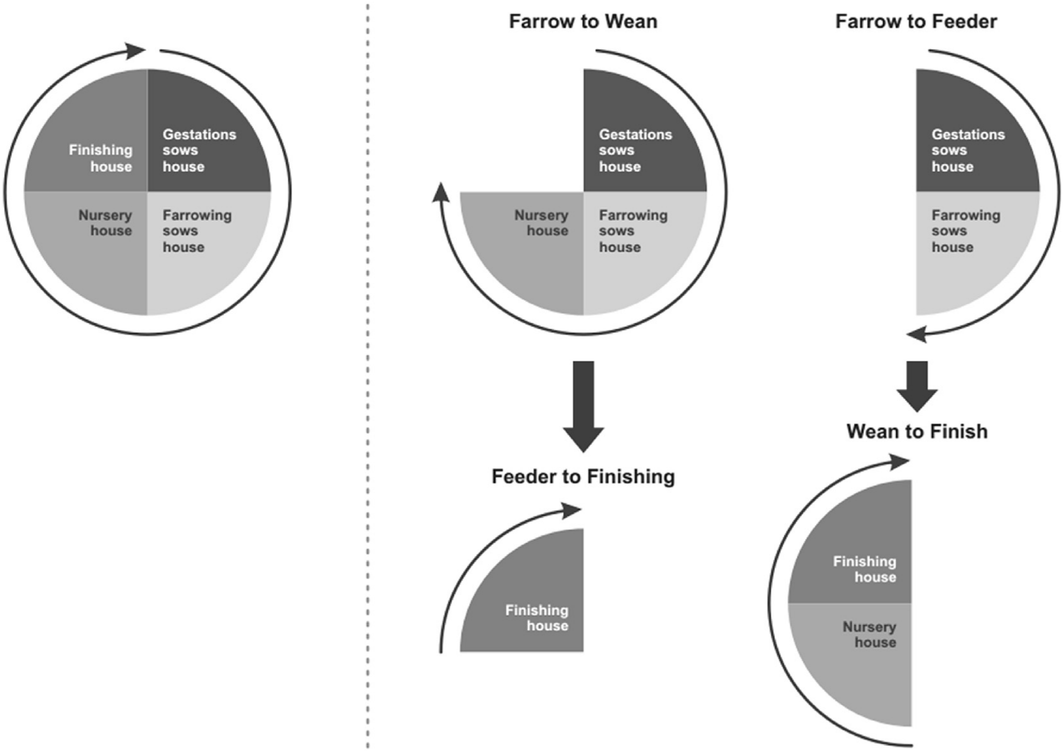

Fig. 1. Differences between swine production in a single and multiples sites and stratified animal production phases.

low cost and simple technology and can be operated in batch and continuous mode (Ford and Fleming, 2012). In a laboratory study of manure with an initial dry matter content between 2% and 4%, settling was observed to reach completion within 1 h. For manure with a dry matter of 6%, the settling time exceeded 4 h. The same characteristics were observed for highly diluted slurries containing 0.5% of dry matter (Hjorth et al., 2010; Ndegwa et al., 2001).

Thus, this study aimed to determine the influence of simplified and inexpensive swine manure solid separation strategies (based on screening and settling) and manure by different swine production phases (gestating and farrowing sows, nursery piglets and finishing pigs) on biogas and methane yield using a standard methodology.

2. Material and methods

2.1. Samples and storage

Representative manure samples (10 L) from a gestation sow house (GSH-a), a farrowing sow house (FSH-a) and a nursery house (NH) were collected from a farrow-to-wean unit with 5900 breeder sows. The samples were collected with 15 (GSH-a), 15 (FSH-a) and 40 (NH) days of storage in the pits inside the swine facilities of a farm in Serranópolis do Iguaçu, Parana-State, Brazil (−25.376720, −54.058157). The finishing house (FH) manure sample (10 L) was collected from a feeder-to-finishing unit with 5000 pigs on a farm in São Miguel do Iguaçu, Parana-State, Brazil (−25.336032, −54.297393). The retention time in the pits (inside the facilities) was 24 h. Manure samples from a gestation sow house (GSH-b) and a farrowing sow house (FSH-b) were collected from a farrow-to-feeder unit with 500 breeder sows on a farm in Concórdia, Santa Catarina-State, Brazil (−27.221780, −52.039789). Both samples were collected with seven days of storage in the pits inside the swine facilities.

None of the sampled sites used any bedding material.

The solid separation strategy and the fractions are presented in Fig. 2.

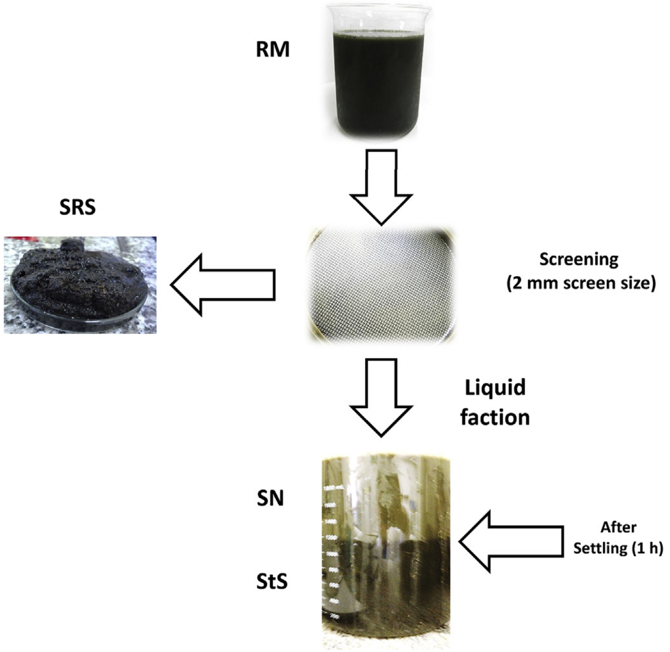

Fig. 2. Screening and gravity solid–liquid separation strategy. Were studied Raw Manure (RM), Solid Retained in Sieve (SRS), Settled Sludge (StS) and Supernatant (SN).

2.2. Biochemical methane potential (BMP)

Anaerobic digestion experiments were performed under mesophilic temperature conditions according to VDI 4630 (2006) in triplicate. The tests were conducted using a 250 mL reactor flask, and the gas volume was measured using eudiometer graduated tubes. The gas production was monitored on a daily basis by displacement of the column of liquid sealant (DIN 38414-8, 1985) in the eudiometer tube, and the dried biogas volume was corrected to 273.15 K and 1013 hPa. All samples were submitted to BMP tests for raw manure (RM), solid retained in sieve (SRS), settled sludge (StS) and supernatant (SN) fractions. The mesophilic anaerobic inoculum was prepared by mixing anaerobic sludge from a reactor that was fed with swine manure and dairy cattle manure (1:1 $v.v^{-1}$) (De Bona et al., 2015). Two weeks prior to the test, the mixture of biomass was acclimatized (37 ± 1 °C) in a CSTR reactor and fed at of 0.3 $kgVS.m^{-3}.d^{-1}$ for seven consecutive days. The inoculum remained seven days without feed to reduce the baseline biogas production (Steinmetz et al., 2014). After the test, biogas production was considered to be stabilized when the daily biogas production was equal to or less than 1% of the total volume (VDI 4630, 2006).

2.3. Biogas analyses

For the biogas composition evaluation (CH_4 and CO_2), the samples were analyzed by infrared and electrochemical sensors (Dräger X-am® 700).

2.4. Solids analysis

Total, volatile and fixed solids were analyzed according to APHA (2012). The samples were dried at 105 °C for the determination of total solids (TS) and calcined at 550 °C for volatile solid (VS) and fixed solid (FS) determination.

2.5. Statistical analysis

The tables list the means and standard deviations of performed experiments in triplicate. All statistical analyses were performed using the GraphPad Prism ver. 3.02 software package. P-values below 0.05 were considered to indicate a significant difference (Pimentel-Gomes, 2009).

3. Results and discussion

3.1. Influence of solid–liquid separation on biogas/methane yield

The first purpose of this study was to determine and understand the influence of solid–liquid separation on the biogas/methane yield. To investigate the impact of different solid fractions and supernatants on biogas and methane yields, the mass balance of volatile solids was determined for all samples (Table 1). The raw manure (RM) concentration was considered to be 100%; each fraction contribution is listed in Table 1.

Table 1
Mass balance of volatile solid for all swine manure studied samples. RM fraction was considered 100%.

Sample	GSH-a	GSH-b	FSH-a	FSH-b	NH	FH
RM %($w.w^{-1}$)	100.00	100.00	100.00	100.00	100.00	100.00
SRS %($w.w^{-1}$)	5.94	21.50	15.35	19.95	15.75	11.83
StS %($w.w^{-1}$)	69.50	48.90	53.66	62.86	18.90	52.06
SN %($w.w^{-1}$)	25.74	29.60	30.54	16.81	67.98	34.63

X/X_0 x 100, where X_0 = RM, X = RM, SRS, STS and SN.

For almost all samples (84%), the StS fraction presented a higher contribution of VS in RM, between 49 and 69%. This effect was not observed for the NH sample, which may be related to the high manure dilution (3.8 kgVS.kg^{-1}) and the storage time in the pits (40 days). For very diluted manure (<0.5% dry matter), settling also decelerates, presumably because fewer of the fine particles are co-precipitated with the larger and faster-settling particles at this low concentration (Hjorth et al., 2010). The storage time may also impact the manure degradation because anaerobic degradation begins during storage. By analyzing dairy manure storage at 20 °C, Browne et al. (2015) observed that biogas production linearly decreased by approximately 0.6 m^{3}biogas.t^{-1} fresh slurry. week^{-1}. This effect can be intensified for swine manure, because it is more biodegradable than dairy manure (Liu et al., 2009).

The volume of the StS fraction represents between 20% and 30% of the RM, which comprises approximately 40–60% of the total methane yield for almost all samples, with the exception of NH (for previously discussed reasons). The methane yield reflects the potential methane production of the fraction (Table 2). For the StS fraction, 1 m^3 can produce from 1.15 to 10.6 m^3 of methane, with an average value of 5.6 m^3 ± 3.3. For the SN fraction, 1 m^3 can produce approximately 0.5–5.8 m^3 of methane, with an average value of 3.1 m^3 ± 2.0. The methane potential of the StS fraction was approximately two times higher than the methane potential of the SN fraction. Although the SN fraction has a higher bioavailable carbon and a higher biogas yield (Nm^3.gVS^{-1}), it has a lower VS concentration. Using separation by settling concentrated liquid (settled sludge) and low-content liquid (supernatant), Deng et al. (2012) observed that the concentrated liquid achieved 18% of the raw manure volume and 61% of the bioavailability carbon and could produce 60% of the total biogas potential.

The SRS fraction, which presented a VS concentration between 10 and 17%, can be employed as a substrate for dry mesophilic biodigestion. Chen et al. (2015) achieved a biogas yield of 0.665 L.g^{-1}VS using fresh swine manure with 20% TS concentration.

For all studied fractions, the SN fraction presented a higher methane yield (Table 2) because the SN fraction presented a higher bioavailability carbon concentration than other fractions (Rico et al., 2012). Sommer et al. (2015) showed that the supernatants obtained by screw pressing and decanter centrifugation had a 16% higher concentration and a 31% higher concentration, respectively, of volatile fatty acids than the solid fraction and of every low lignin, hemi-cellulose and cellulose (>80 g.kg^{-1}) compared with the solid fraction (<280 g.kg^{-1}) (more recalcitrant carbon).

The SN fraction properties may allow its treatment in high-loading rate anaerobic reactors, such as the Upflow Anaerobic Sludge Blanket (UASB). Bergland et al. (2015) investigated swine manure supernatant treated for an UASB reactor and obtained a high biogas yield (0.47 g COD $_{\text{methane}}$.g^{-1} COD $_{\text{manure}}$) when operated from an HRT of 42 to an HRT of 17 h. Consequently, the biogas plant size can be reduced compared to other digester models (covered lagoon, CSTR). Gonzalez-Fernandez et al. (2008) achieved 90% of the methane production for the liquid samples during the first 15 days, whereas 24 days were required for the solid samples; this finding demonstrates the difference in bioavailability between the phases.

3.2. *Kinetic aspects*

The kinetic aspects of BMP tests of all samples are presented in Table 3 and Fig. 3. These results demonstrate the difference in the volatile solids degradability of different fractions in each sample and the contrast among the stratified swine manure samples.

The kinetic studies of RM show that the GSH-a, FH, GSH-b and FSH-b samples produced their maximum daily biogas yield (DBY) on the first day of the test, whereas the FSH-a and NH samples achieved their maximum DBY on the third day of the test, which indicates a lag phase due to possible hydrolysis limitation. This phenomenon may be attributed to the subsequent degradation of insoluble macromolecules, such as crude protein (Xie et al., 2011), due to different feed strategies and metabolic abilities at different growing phases (Zhang et al., 2014).

The SRS fraction presented the lowest DBY rate compared with the remaining fractions of all samples (Table 3). This fraction contained solid particles that were larger than 2.0 mm, which may have contained macromolecular organic matter, such as food

Table 2
Swine manure samples characteristics. Volatile solids, biogas yield, methane yield, methane balance generation and methane capacity of each fraction.

Sample	Fraction	VS (% w.v^{-1})	Biogas yield (Nm^3.kgVS^{-1})	SD	B_0 (Nm^3 $_{CH4}$.kgSV^{-1})	CH_4 balance (Nm^3)	MCMP (Nm^3$_{CH4}$.m^{-3}$_{\text{fraction}}$)
GSH-a	**RM**	0.50	0.326^a	5	0.170	0.86	0.86
	SRS	13.98	0.387	26	0.175	0.05	24.54
	StS	0.78	0.279	12	0.148	0.52	1.15
	SN	0.26	0.406	19	0.201	0.26	0.53
GSH-b	**RM**	2.31	0.577^e	28	0.310	7.15	7.15
	SRS	13.99	0.475	4	0.238	1.17	33.25
	StS	3.29	0.429	5	0.179	2.02	5.88
	SN	0.99	0.900	12	0.582	3.96	5.76
FSH-a	**RM**	0.61	0.860^b	12	0.568	3.44	3.44
	SRS	9.29	0.245	9	0.114	0.11	10.55
	StS	0.90	0.730	18	0.493	1.60	4.44
	SN	0.33	1.157	15	0.737	1.36	2.43
FSH-b	**RM**	2.61	0.479^f	25	0.250	6.53	6.53
	SRS	13.72	0.534	3	0.258	1.34	35.39
	StS	3.28	0.476	4	0.247	4.05	8.11
	SN	1.06	0.524	12	0.309	1.36	3.27
NH	**RM**	0.38	0.970^c	5	0.642	2.45	2.45
	SRS	16.97	0.550	5	0.304	0.18	51.62
	StS	0.62	0.893	11	0.592	0.43	3.69
	SN	0.23	1.086	14	0.651	1.69	1.48
FH	**RM**	2.12	0.474^d	10	0.303	6.42	6.42
	SRS	15.03	0.562	8	0.279	0.70	41.99
	StS	3.68	0.467	4	0.287	3.18	10.59
	SN	1.47	0.522	4	0.342	2.51	5.03

[*] **a,b,c,d, e and f** means statistical significant difference ($p < 0.05$); **SD**: Standard Deviation; **B_0**: Methane yield; **CH_4 balance:** Methane contribution of each studied fraction (RM = SRS + StS + SN); **MCMP:** Maximum capacity of methane production from each fraction.

Table 3
Maximum daily biogas yield, occurrence day batch test time.

Sample	Fraction	Maximum DBY (NmL. $gSV^{-1}.d^{-1}$)	Day	Batch test time (d)
GSH - a	**RM**	95.89	1	21
	SRS	35.89	1	27
	StS	90.57	1	21
	SN	78.58	1	20
GSH-b	**RM**	138.5	1	29
	SRS	80.66	9	25
	StS	123.82	1	32
	SN	229.30	1	24
FSH - a	**RM**	171.50	3	21
	SRS	58.60	1	26
	StS	168.24	3	27
	SN	277.39	2	17
FSH-b	**RM**	117.25	1	21
	SRS	91.82	1	29
	StS	117.11	1	27
	SN	150,38	1	21
NH	**RM**	234.46	3	20
	SRS	124.24	1	27
	StS	245.79	3	21
	SN	201.59	1	17
FH	**RM**	129.25	1	21
	SRS	82.47	2	26
	StS	123.37	1	21
	SN	115.90	3	17

Maximum DBY: Maximum daily biogas yield; **Day:** Occurrence of maximum daily biogas yield; **Batch teste time:** When the daily biogas production becomes equal to or less than 1% of the total volume produced.

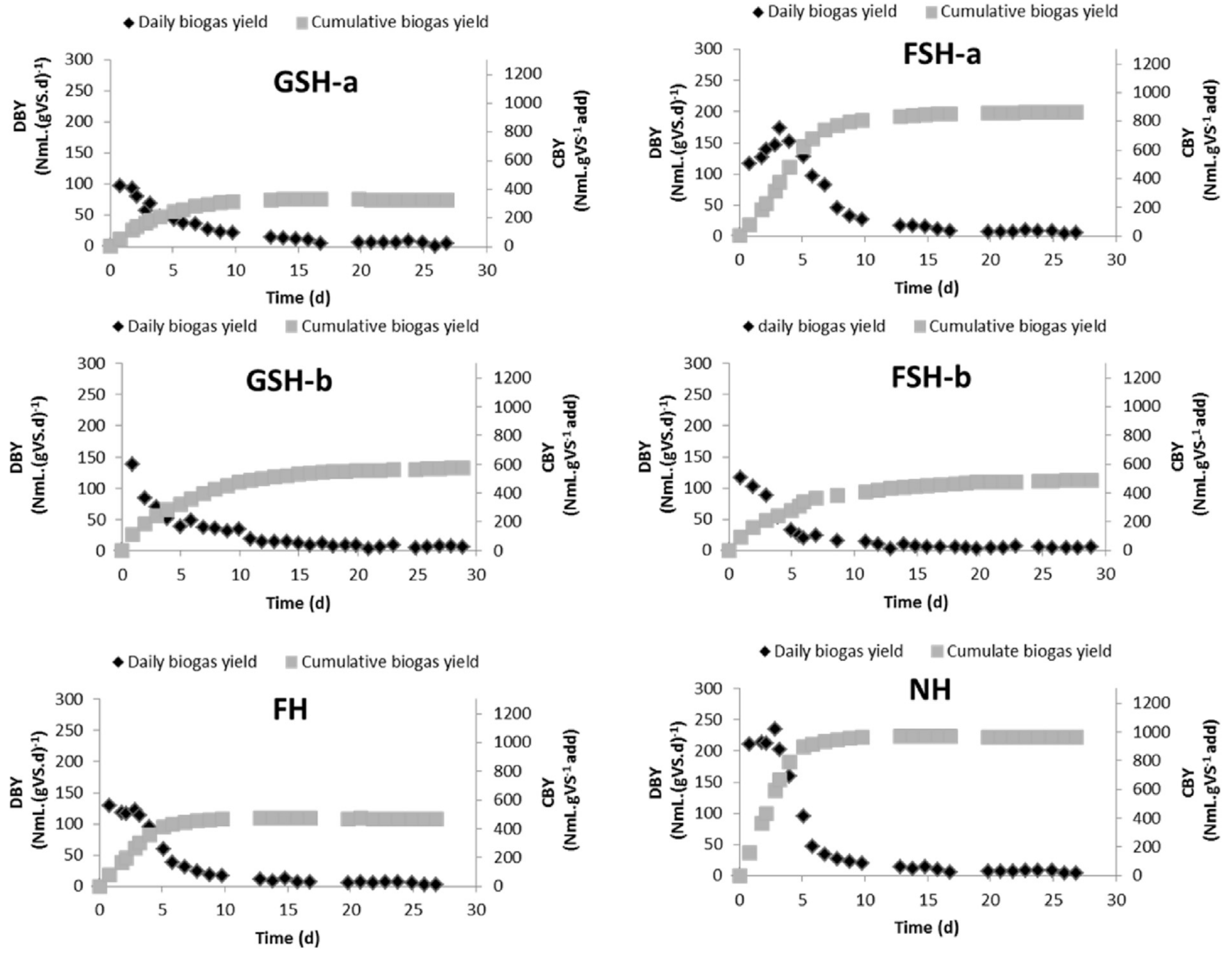

Fig. 3. Stratified swine manure samples cumulative biogas yield (CBY) and daily biogas yield (DBY).

residues and nondigested feed, for which anaerobic degradation is difficult (Zhang et al., 2014). A few alternatives are available for improving the DBY of manure samples, such as ultrasonic, thermal, microwave, chemical and physical pretreatment. These techniques seek to achieve particle size reduction, solubilization and biodegradability enhancement (Carlsson et al., 2012).

The stabilization of all tests occurred between 17 and 32 days (Table 3 and Fig. 3). For all samples, the SN fraction was rapidly stabilized. Consequently, the size of the plant and facilities in which the SN fraction is treated should be reduced compared with the requirements for SRS and StS (lower requirement for HRT).

3.3. Influence of stratified swine manure on biogas/methane yield

Significant differences ($p < 0.05$) in biogas yield between the swine manure samples from the stratified swine production phases were observed in this study. The differences in VS bioavailability (Table 2) for anaerobic microorganisms among different types of swine manure samples may be caused by different feed strategies and nutrient digestibility, as well as differences in manure management within the facility (Brooks et al., 2014; Gopalan et al., 2013).

The VS concentration in RM for GSH-a, FSH-a and NH was less than the VS concentration indicated in the literature, 1–2% VS, (Deng et al., 2012). These data are related to management problems pertaining to the excessive use of water in swine housing (water leaking in drinker devices, washing and general leaks) (Tavares et al., 2014). Another related factor is the high retention time in the pits inside the facilities (15, 15 and 40 days, respectively), which favors organic matter degradation and causes decreased VS concentration (Kunz et al., 2009-b). Another factor observed for these fractions is the low maximum capacity of methane production (MCMP) of RM compared with other samples due to high dilution.

The highly diluted swine manure contain little carbon to ensure an economically attractive methane yield and requires compensation from larger digesters with longer hydraulic retention times (Hamelin et al., 2011). Longer storage times in the pits contribute to a reduction in volatile solids in manure. Popovic and Jensen (2012) obtained a 40% reduction in the VS concentration when the storage time exceeded eight weeks. This result indicates the necessity to improve the management of manure for GSH-a, FSH-a and NH.

The biogas yields showed differences between the evaluated stratified swine manure samples (Table 2 and Fig. 2). The difference in the biogas production of the samples may be attributed to differences in the feeding techniques that are applied in the swine industry. Maximum feed wastage in weaner pigs can be 15% ($w.w^{-1}$), which are known to have poorer large intestine fermentation, causing relatively poor feed conversion. Adult sows and finishing pigs have improved hind gut fermentation (Shi and Noblet, 1993).

4. Conclusion

The separation of solids by screening and gravity settling is an interesting possibility because the fractions presented different biogas and methane yields. The supernatant fraction presented more bioavailable organic matter than other studied fractions and achieved the highest biogas and methane yield (0.406–1.157 $Nm^3_{biogas}.kgVS^{-1}$). Although the settled sludge fraction contains higher volatile solid concentrations than other liquid fractions, it presented the lowest biogas yield (0.279–0.893 $Nm^3.kgVS^{-1}$), with difficult degradation (kinetic aspects).

Differences in biogas and methane yield exist among the swine effluents from different production stages. The differences are related to the production stages (feed and conversion) and the effluent management inside the facilities.

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