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Effect of substrate volume in a digester on biogas production from animal excreta

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Abstract
Three animal excreta (cow dung, poultry excreta and swine dung) were digested in four substrate volumes (50, 60, 70 and 80% of the digester volume) in a 3 × 4 factorial design. Substrate temperature, pH and biogas yield were monitored during the 63-day study. The results showed that excreta type affected ($p \leq 0.05$) pH and biogas yield with poultry excreta producing the highest yield (11.8 $cm^3\ kg^{-1}$ VS fed day^{-1}). Although the biogas yields from the different substrate volumes were not significantly ($p > 0.05$) different, 50% appeared not only to have produced the highest yield (7.89 $cm^3\ kg^{-1}$ VS fed day^{-1}) but maintained a constant higher yield during digestion. The study therefore concluded that cow dung, poultry excreta or swine dung slurry loaded between 50-80% of a digester volume would produce apparently the same biogas yield.

Keywords: Substrate volume, animal excreta, biogas yield

Introduction
Biogas is an energy source that is used for the production of heat and electricity or as fuel in cars. Its generation from organic waste under anaerobic conditions has become attractive in most developing and developed countries of the world. Biogas production is a three-stage biochemical process involving hydrolysis, acidogenesis/caetogenesis and methanogenesis (Ofoefule *et al.*, 2009). Biogas consists of methane (55-65%), carbon dioxide (30-45%), traces of hydrogen sulphide and a fraction of water vapour (Kapdi *et al.*, 2008). Factors relating to anaerobic digestion and biogas production ranging from feed stocks (Ogunwande *et al.*, 2015), co-digestion (Ogunwande, *et al.*, 2013), temperature (Chae*et al.*, 2008), pH and buffering capacity (Kim *et al.*, 3003), mixing (Gomez *et al.*, 2006), reactor design (Nielsen *et al.*, 2004) to pre-treatments (Ofoefule *et al.*, 2009) have been extensively discussed. However, information about the relationship between substrate volume (as a percentage of digester volume) and biogas yield is still scanty. Many anaerobic digestion studies have been carried out at arbitrarily selected substrate volumes and the effects on biogas yield have not been adequately investigated. In this study, a range of substrate volumes was selected to digest some selected animal excreta with a view to assessing the effect on anaerobic digestion and biogas yield.

Materials and Methods
Materials and digestion set up
The study was conducted at the Department of Agricultural and Environmental Engineering, Obafemi Awolowo University, Ile-Ife, Nigeria. The experiment was a 3 × 4 factorial design with

3 animal excreta (cow dung (CD), poultry excreta (PD) and swine dung (SD)) and 4 substrate volumes (50, 60, 70 and 80% of digester volume). Fresh animal excreta were collected from the cattle barn, layer house and pig pen at the Obafemi Awolowo University Teaching and Research Farm. The digestion set up comprised digesters, water tanks and water collectors. The digesters were adapted using cube-shaped 25 dm^3 plastic kegs and were positioned to give 2.50 × 4.65 dm^2 surface and 2.15 dm height dimensions. A drain plug was fitted to the base of each digester for collection of samples for pH analysis. Each digester had a digital thermometer probe fitted to it for temperature measurement. Similarly, the water tanks and water collectors were adapted using cube-shaped10 dm^3 and 5 dm^3 plastic kegs respectively. A rubber hose was used to connect each digester to the water tank and the water tank to the water collector.

Analytical procedure and anaerobic digestion

Samples from the excreta were analysed for Total Solids (TS) (oven drying at 105 °C for 24 h); Volatile solids (VS) (ashing of TS at 550 °C for 5 h); Total Nitrogen (TN) (regular-Kjeldahl method; Bremner, 1996); pH (1:10 w/v sample: water extract, using a digital pH meter). The Total Carbon (TC) content was estimated from the ash content according to the formula developed by Mercer and Rose (1968):

$$TC\ (\%) = [100 - Ash\ (\%)]/1.8$$

After the moisture content determination, each excreta sample was diluted with clean tap water to 8% TS as recommended by Zennaki *et al.* (1996), agitated vigorously and poured through a 6 mm plastic mesh to remove gross solids. The digesters were loaded once at the start of the experiment to the different volumes and each treatment was replicated thrice. The biogas produced was collected by water displacement method (Archimedes' principle) and measured using a calibrated cylinder. The digesters were manually agitated twice daily (at twelve hours interval) to avoid long period settlement of the substrates and ensure uniform distribution of microorganisms and heat within the substrates. Ambient and substrate temperatures and biogas yields were measured daily while substrate pH was measured weekly.

Statistical analysis

Data collected were subjected to two-way analysis of variance (ANOVA) using the GLM procedure of the Statistical Analysis Systems software (SAS, 2002) to compare variations in substrate temperature, substrate pH and biogas yield. Where significance was indicated at $p \leq 0.05$, Duncan's Multiple Range Test was used to separate the means.

Results and discussion

The carbon to nitrogen (C:N) ratios of fresh poultry excreta and swine dung (Table 1) were within the ratios recommended for stable biological conversions (Kayhanian and Hardy, 1994) and the sustainability of organic feeds for methanogenesis (TERI, 1985). Cow dung had the highest initial C:N ratio and pH. The experiment was terminated at 63 days when most treatments had stopped producing biogas.

Table 1 - Initial properties of the excreta types

Excreta type	Properties (dry weight basis)				
	pH	VS (%)	TC (%)	TN (%)	C:N ratio
Cow dung	7.80	95.7	53.2	1.15	46.2
Poultry dropping	6.80	61.1	33.9	1.23	27.6
Swine dung	6.70	92.1	51.2	1.96	26.4

VS: volatile solids, TC: total carbon, TN: total nitrogen

Table 2 - ANOVA results showing the effects of substrate volume and excreta type on temperature, pH and biogas yield

Parameter	Source	Df	SS	MS	*F*-value	Pr>F
Temperature	SVo	3	3.266	1.088	0.190	0.899
	ET	2	3.721	1.860	0.330	0.722
	SVo*ET	6	7.566	1.261	0.220	0.965
	Error	24	135.166	5.631		
pH	SVo	3	0.007	0.002	0.540	0.661
	ET	2	0.590	0.295	65.040	<0.001
	SVo*ET	6	0.008	0.001	1.300	0.932
	Error	24	0.109	0.005		
Biogas	SVo	3	37.268	12.423	0.260	0.850
	ET	2	539.838	269.919	5.760	0.009
	SVo*ET	6	227.732	37.955	0.810	0.573
	Error	24	1125.243	46.885		

SVo: substrate volume, ET: excreta type, Df: degrees of freedom, SS: sum of squares, MS: mean of squares

Substrate temperature

The ambient and substrate temperatures during digestion ranged from 20.7 to 33.5 ^{o}C and 24.7 to 31.7^{o}C respectively. The substrate temperatures were within the mesophilic range of 25-35 ^{o}C considered optimal for the support of biological reactions (Tchobanoglous *et al.*, 2003). The results showed that neither substrate volume nor excreta type had significant ($p > 0.05$) effect on substrate temperature of the treatments (Table 2).

The daily temperature values recorded were averaged weekly and presented as shown in Figure 1. The profiles followed the same pattern in all the treatments. There were temporary increase and decrease in temperatures during weeks 2 and 3, respectively in all the treatments. The successive weeks showed gradual increase with a slight decrease during week 5. Only poultry excreta treatments had obvious distinction among the treatments with

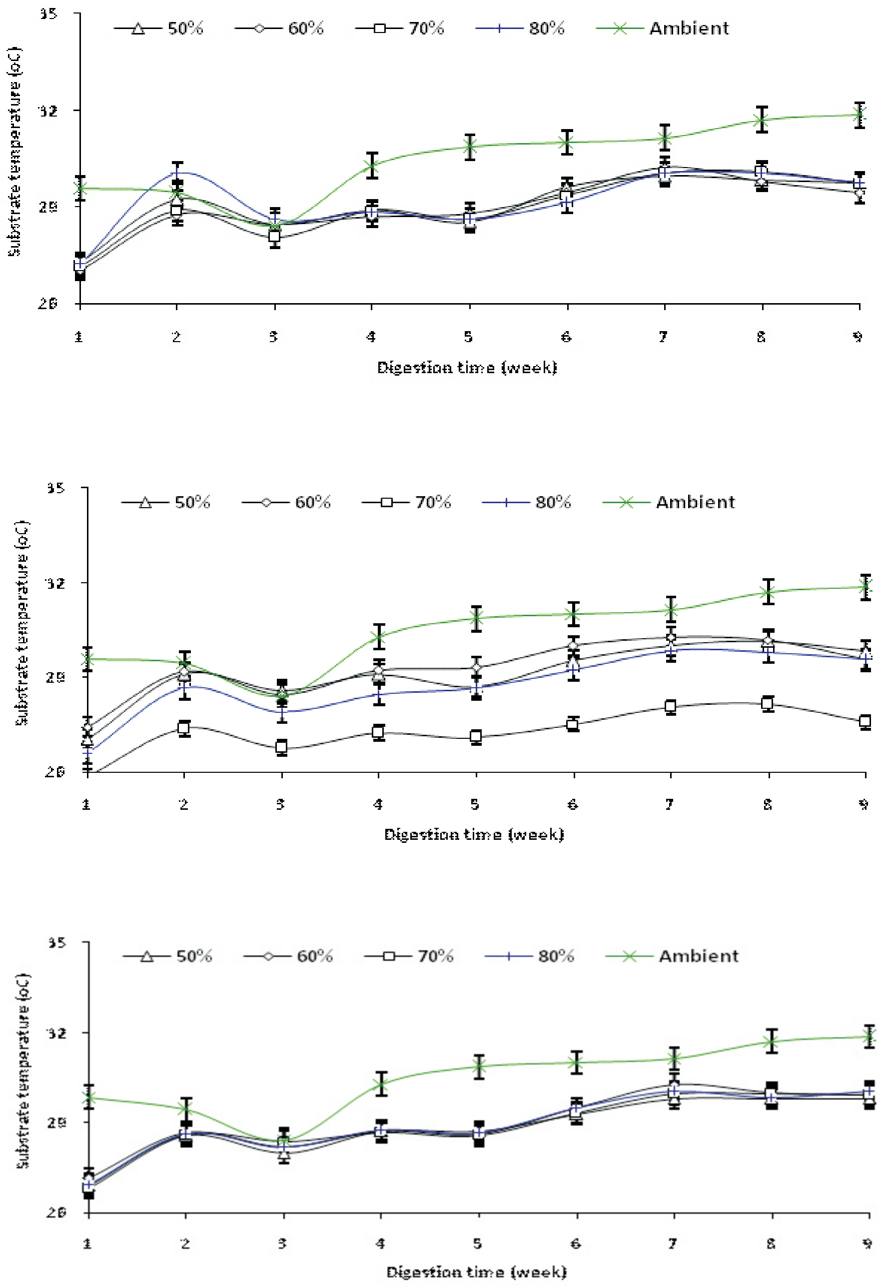

Figure 1 - *Profile of weekly temperature during digestion of (a) Cow dung, (b) Poultry dropping and (c) Swine dung.*

Table 3 - Significant means separation using the Duncan's Multiple Range Tests.

Parameter	Excreta type			Substrate Volume (%)			
	CD	PD	SD	50	60	70	80
Temperature (^oC)	29.1^a	29.2^a	28.5^a	29.0^a	29.1^a	29.1^a	28.4^a
Ph	7.07^a	7.35^b	7.35^b	7.26^a	7.28^a	7.25^a	7.25^a
Biogas (cm^3 kg^{-1} VS fed day^{-1})	2.74^a	11.8^b	4.96^a	7.89^a	5.06^a	6.27^a	6.83^a

Superscripts with the same letters along the same row are not significantly different at p = 0.05.
CD: cow dung, PD: poultry dropping, SD: swine dung

respect to the temperature profiles (Figure 1b), with 70% substrate volume treatment maintaining the least temperature during digestion. The daily temperatures during digestion can be used as indicator of microbial activities. The fluctuations reflected active microbial activities during biodegradation.

Significant ($p \leq 0.05$) correlation was observed between ambient and substrate temperatures in almost all the treatments (Table 4), indicating possible heat exchange through the digester walls. Similarly, substrate temperature and pH had significant ($p \leq 0.05$) negative correlation, indicating that as the pH decreased, temperature increased and vice versa.

Substrate pH

The pH values fluctuated between 5.97 and 7.8, 6.3 and 8.57 and 6.2 and 7.63 in cow dung, poultry excreta and swine dung treatments, respectively during digestion (Figures 2a,b and c). The range of pH showed that the substrates were digested within the range of 6-8 considered suitable for bacteria involved in anaerobic digestion. It was also observed that substrate volume did not affect ($p > 0.05$) substrate pH but excreta type did ($p \leq 0.05$) (Table 2). Incidentally, poultry excreta and cow dung had approximately the same and higher pH values during digestion (Table 3). The pH profiles of treatments in each excreta type followed the same pattern (Figure 2). The pH value of swine dung

Table 4 – Coefficient of determination (R2) from pair-wise correlation of parameters

Substrate volume (%)	Correlated parameters			
	AT/ST	ST/pH	ST/BY	pH/BY
50	0.663a	-0.708a	0.003	0.085
60	0.678a	-0.660a	0.108	0.385
70	0.778a	-0.723a	0.333	0.361
80	0.497	-0.508	0.159	0.095

aValues significant at p = 0.05.
AT= ambient temperature, ST= substrate temperature, BY= biogas yield.

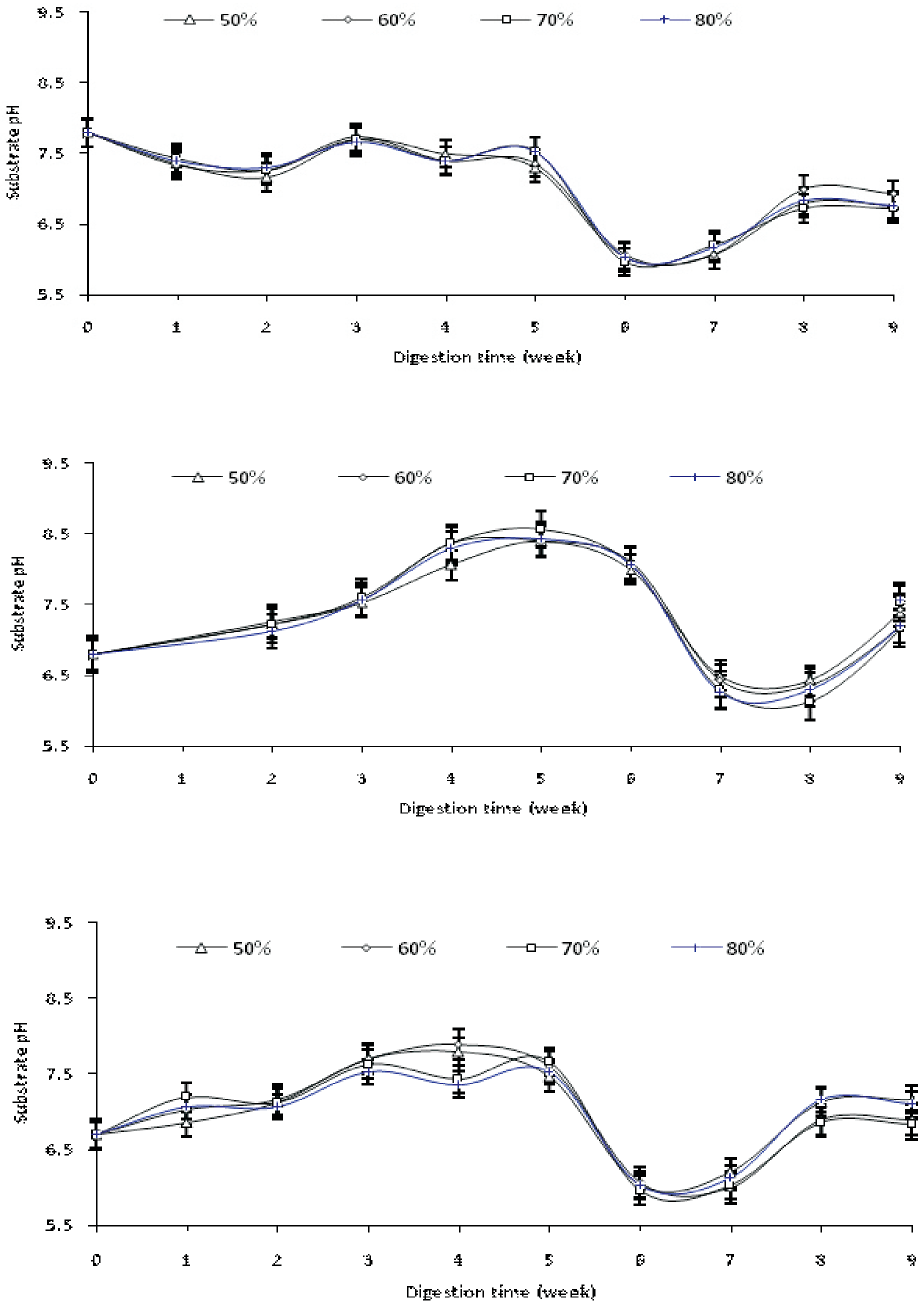

Figure 2 - Profile of weekly pH during digestion of (a) Cow dung, (b) Poultry excreta and (c) Swine dung.

treatments (Figure 2c) increased gradually from initial (6.70) to peak (7.37-7.90) during weeks 4 and 5 before dropping to least (5.97-6.21) during weeks 6 and 7. Similarly, the pH value of poultry excreta treatments (Figure 2b) increased gradually from initial (6.80) to peak (8.40-8.57) during week 4 before dropping to least (6.14-7.40) during weeks 7 and 8. The pH value of cow dung treatments (Figure 2a) exhibited a slightly different trend. Slight fluctuations were recorded before dropping to least values (5.97-6.07) during week 6. The increase in pH during digestion could be attributed to subsequent transfer and consumption of volatile fatty acids during methanogenesis while the decrease implied the production of volatile fatty acids (Cuzin *et al.*, 1992).The attainment of pH values >5 during digestion showed that there was efficient methane production (Jain and Maattiasson, 1998). The final pH values (6.73-7.33) were within the range of 6.0-8.5 for organic matter compatibility with most plants (Lasaridi *et al.*, 2006).

Biogas yield

Biogas production started after about 2-12 days lag period. The lag may have been due to the time needed by the microbial flora in the excreta to acclimatize to the new environmental conditions. Averagely, the lag varied from 8, 9, 10 and 11 days for 60%, 80%, 50% and 70% substrate volume treatments respectively. Across the excreta, the lag was 6, 11 and 11 days for poultry excreta, swine dung and cow dung, respectively. The results showed that excreta type had significant ($p \leq 0.05$) effect on biogas yield but substrate volume did not (Table 2). Poultry excreta produced the highest yield (11.8 cm^3 kg^{-1} VS fed day^{-1}) while cow dung and swine dung produced significantly the same ($p > 0.05$) yield (Table 3). The high yield observed in poultry excreta compared to cow dung and swine dung substrates may be attributed to the high degree of biodigestibility of the poultry excreta (Odeyemi, 1982). Although substrate volume had no significant ($p > 0.05$) effect on the biogas yield, the mean values showed that 50% produced the highest yield while 60% produced the least (Table 3). Low and non-significant ($p > 0.05$) correlation was established between substrate temperature and biogas yield and pH and biogas yield (Table 4). This showed that none of the parameters affected biogas production during digestion. The daily biogas production fluctuated repeatedly, reflecting microbial activities during digestion. All the treatments recorded varying number of days with no gas production, which may be due to the extremely cold weather and fluctuating temperatures during the period of the study. Similar results were observed by Adanikin *et al.* (2017). However, poultry excreta picked up faster and this can be attributed to possibility of high degree of organic carbon available for biodegradation. The daily yields recorded were averaged weekly and presented in Figures 3a, b and c. The weekly yields exhibited a sinusoidal pattern and peaked at different weeks. The varying peak periods were attributed to the differences in the degree of biodigestibility of the animal excreta (Odeyemi, 1982).

The average cumulative yields of the substrate volumes are presented in Figure 4. Substrate volume of 70% had the longest lag of 11 days followed by 50% which had 8 days. Substrate volumes of 80% and 60% had 4 and 3 days lag respectively. Biogas production picked up faster in 60% substrate volume but slowed down at day 6

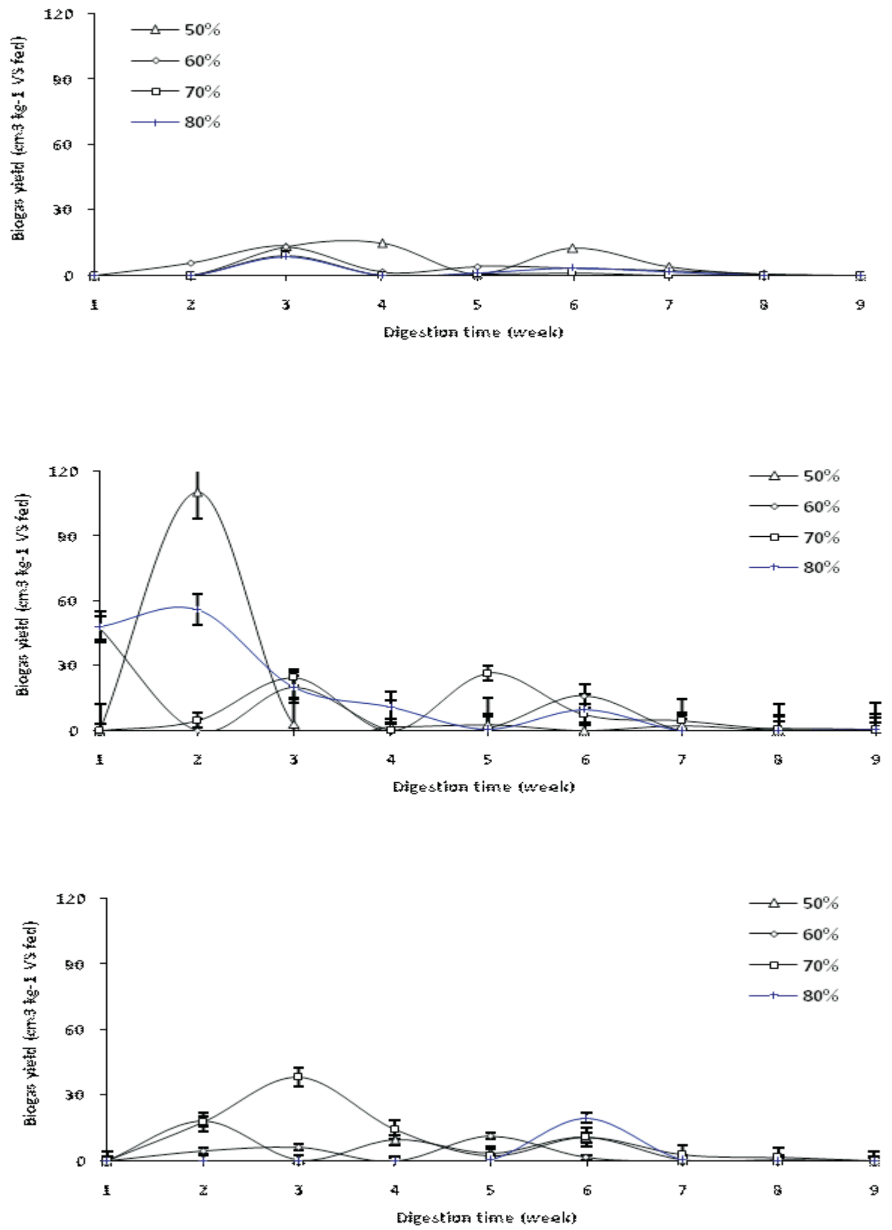

Figure 3 - Weekly biogas yield during digestion of (a) Cow dung, (b) Poultry excreta and (c) Swine dung.

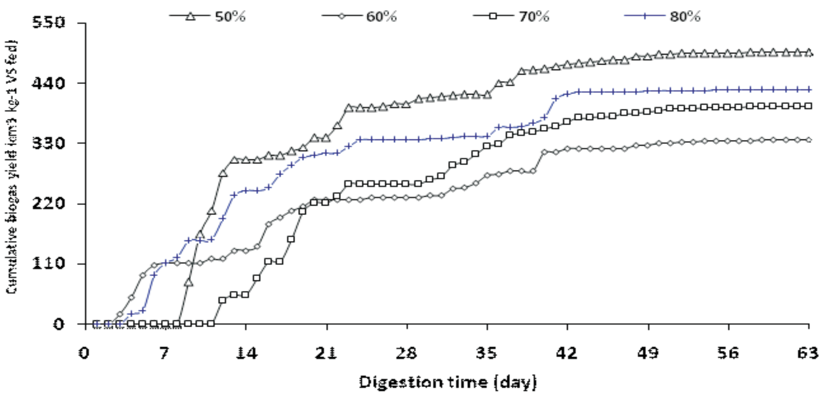

Figure 4 - Cumulative biogas yield from the substrate volumes during digestion.

through day 14. At the start of biogas production by day 9 in 50% substrate volume, production picked up rapidly and was consistently higher than in other treatments. After the 11 days lag, production picked up in 70% substrate volume, rose rapidly and overtook the production in 60% substrate volume by day 22 till the end of digestion.

Conclusion

The results showed that excreta type affected pH and biogas yield. Poultry excreta produced the highest biogas yield. Although the biogas yields from the different substrate volumes were not significantly different, 50% substrate volume appeared to have produced the highest biogas yield. Interestingly, the cumulative yield showed that 50% substrate volume maintained the highest yield from the early days of digestion. In conclusion, 50-80% substrate volume of a digester would apparently yield the same level of biogas.

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