OPTIMUM ANAEROBIC DIGESTION ORGANIC LOADING RATES

Rus, E.[1,2] and Winter,P.[1] Smith, S.R.[2]
[1]Thames Water, [2]Imperial College London, UK
Correspondence Author Tel: +44 (0) 7747 640614
Email: Ester.RusPerez@thameswater.co.uk

Abstract

Solids loading rate is a basic operational control parameter for sludge anaerobic digestion (AD) systems, yet the quantitative effects of loading rate on the dynamics, efficiency and stability of the AD process are poorly understood. The aim of this study was to determine the effects of different sludge loading rates on the performance of conventional mesophilic AD. Controlled experiments were performed using an automated laboratory digester to measure the effects of different loading rate conditions on net gas production. The effects of under loading as well as overloading on the net performance of the AD process were considered. The results showed that the process stability was maintained at organic loading rates of 1.5, 2, and 2.5 kg VS/m^3/d. Specific gas production increased in linear response to organic loading rate and improved on average by 17 % from 453 m^3/t VS at the lowest feed rate equivalent to 1.5 kg VS/m^3/d to 529 m^3/t VS at the highest feed rate equivalent to 2.5 kg VS/m^3/d. A wider range of organic loading rates was assessed using batch digestion.

Keywords

Anaerobic digestion, organic loading, biogas.

Introduction

Anaerobic digestion (AD) is one of the most well-established and cost-effective methods for sewage sludge treatment. Renewable energy generation, rising energy prices, increasing production of sludge, due to population pressure, and tighter requirements for its recycling to agriculture are important challenges for the wastewater industry. Therefore, improving the efficiency of Water Utility assets for sewage sludge treatment, and AD in particular, is critical to maximise resource recovery and sludge recycling.

Solids loading rate is a basic operational control parameter for sludge AD systems, yet the quantitative effects of loading rate on the dynamics, efficiency and stability of the AD process are poorly understood.
This project explores the impact of organic loading rate (OLR) on biogas production efficiency and stability of the AD process to determine the optimum OLR to maximise gas production.

Materials and Methods

Experimental Procedure

Laboratory scale automatic digesters were used for the experimental investigations (Figure 1). The auto-digesters consisted of a reservoir, anaerobic digester and waste tank each with a capacity of 60 litre and three automatic systems were operated during the experiment. The digesters, developed by Glamorgan University, were pump-fed several times per day with raw sludge. On-line monitoring of biogas was conducted by infrared gas cards for CO_2 and CH_4 and by gas flow measurement using a pressure differential mass flowmeter. The accuracy of the gas cards was confirmed with calibration gases at regular intervals. The mass flowmeter was calibrated with 100% CH_4 calibration gas and a factor of 0.848 was applied to correct for a typical biogas composition of 65% CH_4 /35% CO_2. Gas flow calibration was carried out through a rotameter (100% CH_4) to avoid systematic errors in pressure differential by the serial application of the on-line gas monitors. The digestion sequence and on-line monitoring was controlled using LabView 8.6 Graphical Programming (National Instruments, 2008).

Feeding was on an 8 hour cycle; 1 kg of sludge from the digester was withdrawn at each feed cycle, resulting in an overall retention time (RT) of 16.5 days. The digestion temperature was maintained at 37 °C. The temperature of the sludge in the feed tank was cooled to 5 °C. Digested sludge pH and temperature, gas production and composition were monitored on-line. Data were recorded automatically at intervals of 3 minutes. The feed and waste reservoirs were emptied on a weekly basis and cleaned thoroughly to avoid cross contamination.

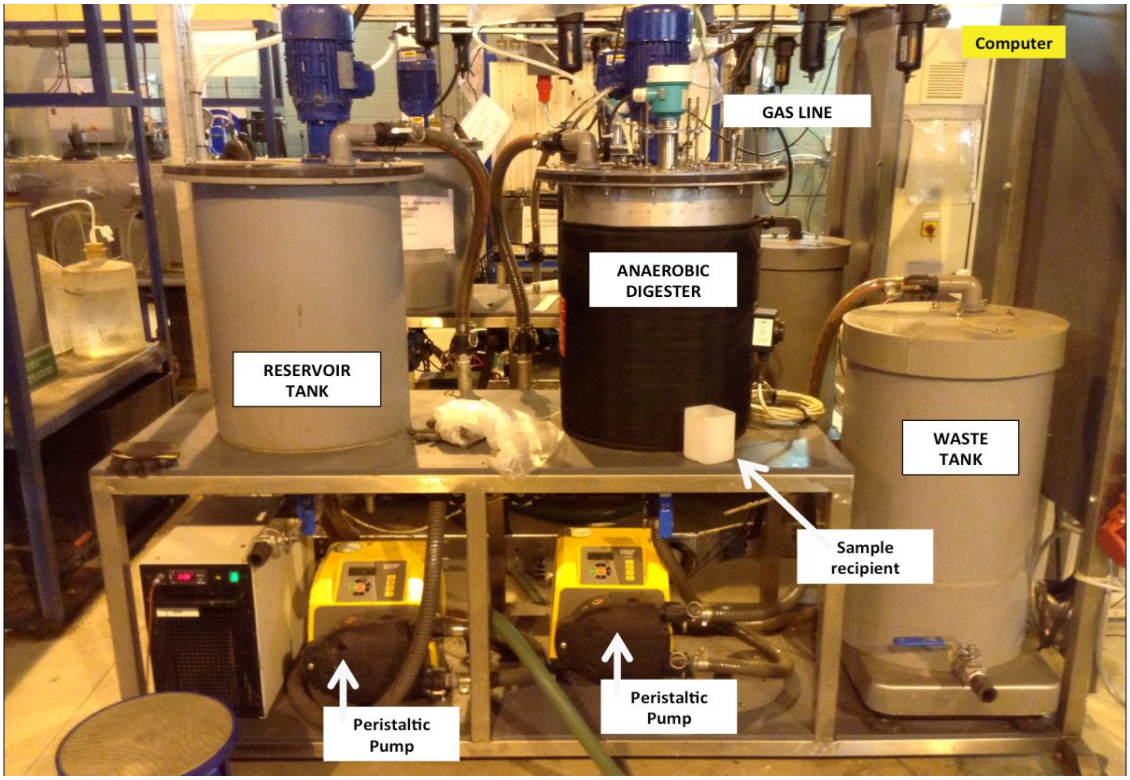


Figure 1: Laboratory scale automated anaerobic digesters

Dewatered primary sludge (PS) and surplus activated sludge (SAS) were collected from the gravity belt thickeners at Reading Wastewater Treatment Works at weekly intervals. The collected PS and SAS samples were mixed at a solids ratio of 3:2, respectively, and diluted with water to obtain the target load (it was assumed that the volatile solids (VS) content was 77%, which was verified as a consistent and representative value). The reservoir tanks received 40L of the blended sludge mixture, which was sufficient to supply the experiment for one week.

Samples of digested sludge output were collected twice per week and were tested for dry solids (DS) and volatile solids (VS) contents, alkalinity, pH and the concentrations of ammonia and total volatile fatty acids (VFAs).

During the first 14 days of the experiment, to achieve an equilibrated response, all of the automatic digesters received the same OLR equivalent to 2 kg VS/m^3/d.
After this initial period, the loads where changed to 1.5, 2, and 2.5 kg VS/m^3/d for each digester respectively. This second experimental period run for 46 days.

Laboratory Scale Batch Digesters

The AMPTS II apparatus (BIOPROCESS CONTROL) performs on-line measurements of bio-methane flows produced from AD (Figure 2) and was used to examine the effects of a broader range of organic loading rates than was applied to the auto-digesters. The OLRs elected where 1.0, 3.0, 4.0, and 5.0 kg VS/m^3/d.

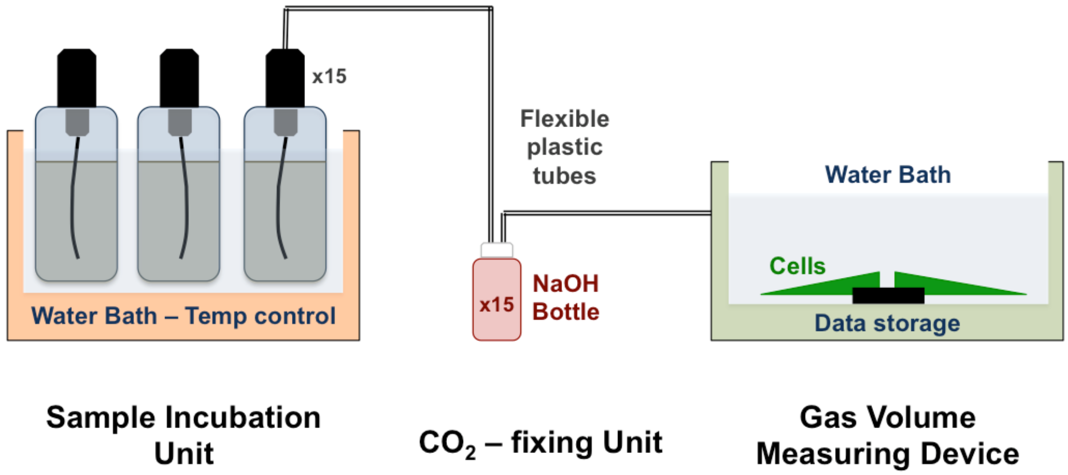


Figure 2: Diagram of laboratory scale batch digesters

Feed sludge was prepared following the procedure described above. Fifteen experimental flasks (400 ml) were prepared in triplicates of each OLR treatment; three replicate flasks were also established containing digested sludge inoculums as the control reference treatment. The ratio of inoculum to feed sludge was 2:1. This was chosen based on previous work done by Thames Water.

Model fitting to laboratory scale batch reactors

Two models, an exponential and a logistic function, where fitted to the accumulative gas yield to describe the rate of gas yield during the batch AD experiment. The models had the form:

Exponential:

$$N = N_{max}(1\text{-}exp^{-kt}) \qquad (12)$$

Where **N** is CH_4 yield in kg VS/m^3/d, N_{max} (kg VS/m^3/d) is the maximum CH_4 yield, ***k*** is the reaction rate constant (days^{-1}), and ***t*** is time.

Logistic:

$$N = N_{max} / (1+exp^{(a-kt)}) \qquad (13)$$

Where ***a*** is an equation constant.

Results

Bench scale automated digesters

Digester Equilibrium

The automatic digesters were equilibrated for the first 14 days of the experiment at the same OLR equivalent to 2 kg VS/m^3/d. Routine monitoring parameters (Table 1) demonstrated approximate equivalency and steady-state was maintained between the digesters.

This was confirmed by one-way analysis of variance (ANOVA) of the gas production and volatile solids destruction (VSD) data, which showed there was no statistically significant (P>0.05) difference between the digesters. The average VSD was 44.2% and the mean gas composition was 37.55±0.45% of CO_2 and 64.54±0.51% of CH_4. The VFA/Alkalinity ratio was below 0.4 and indicative of stable digestion conditions.

Table 1: **Average and standard deviation of OLR, pH, VFA concentration, and alkalinity during the initial steady-state period**

	Actual Load (kg VS/m³/d)	pH	VFA feed (mg/L)	VFA digested (mg/L)	Alkalinity (mg/L)
Digester 1	1.91±0.11	7.3±0.04	2005	188	6601.9±398.2
Digester 2	1.91±0.08	7.3±0.04	1642	178	6543.3±58.0
Digester 3	1.93±0.08	7.4±0.01	1775	203	6668±315.4

	CO_2 (%)	CH_4 (%)	Absolute Gas Yield (L/d)	Specific Gas Yield (m³/tVS fed)	Specific Gas Yield (m³/tDS fed)
Digester 1	38.0±0.9	64.9±1.6	48.7±4.5	515.6±56.7	398.9±43.2
Digester 2	37.6±0.5	64.0±1.4	47.5±5.2	506.7±53.7	386.8±43.9
Digester 3	37.1±1.1	64.7±1.9	47.1±5.3	495.9±55.2	368.6±55.4

OLR and digester stability

Table 2 shows the target and actual average OLRs for the three different treatments during the experimental period together with the mean and standard deviation of DS and VS.

Table 2: **Change in OLR for second stage (Target and actual loads), and summary of DS and VS values for the second stage of the experiment at different actual OLR.**

	Load (kg/m³/d) 1st stage	Target Load (kg/m³/d) 2nd stage	Actual Load 2nd stage (kg VS/m³/d)	DS (%)	VS (% of DS)
Dig 1	2	1.5	1.53±0.12	3.29 ± 0.26	77.0 ± 0.96
Dig 2	2	2.0	1.97±0.22	4.20 ± 0.43	77.3 ± 1.49
Dig 3	2	2.5	2.38±0.16	5.12 ± 0.34	76.7 ± 1.22

Digester stability was maintained by the different OLRs and the process pH, alkalinity and VFA profiles were consistent with recommended values for AD (Mara and Horan, 2003;

Tchobanoglous *et al.,* 2003). The VFA/alkalinity ratio was <0.4 in all cases and no statistically significant difference in VSD was detected by ANOVA. Parameter mean values and standard deviations are listed in Table 3.

Table 3: **Summary of the actual loading rate (kg VS/m³/d), pH values, alkalinity (mg/L) of digested sludge, VFA concentration (mg/L) in feed and digested sludge, and VSD (%) estimated by mass balance and Van Kleeck Formula at different OLRs.**

	Actual Load (kg/m3/d)	pH	Alkalinity Digested Sludge (mg/L)	VFA Feed Sludge (mg/L)	VFA Digested Sludge (mg/L)	VSD Van Kleeck (%)	VSD Mass Balance (%)
Digester 1	1.53±0.12	7.1±0.12	4267±1384	1070±667	166±115	41.38±4.31	42.79±5.71
Digester 2	1.97±0.22	7.1±0.10	4762±1585	1278±551	202±81	47.24±4.94	50.39±3.64
Digester 3	2.38±0.16	7.3±0.07	5863±1830	2151±1096	252±136	43.57±3.16	48.08±2.69

Absolute gas production

As would be expected, increasing OLR significantly increased (*P*<0.001) the absolute gas yield (Figure 3).

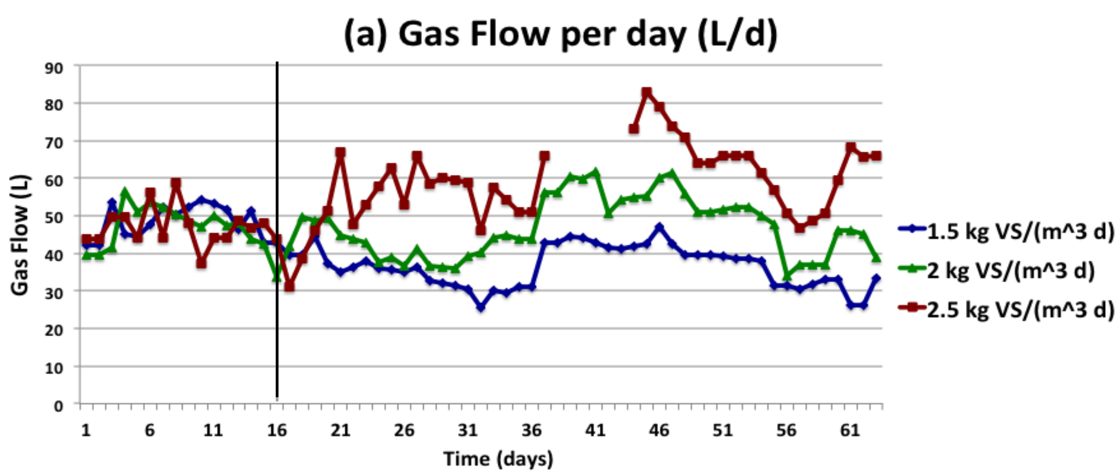


Figure 3: **Absolute gas production in L/d. First 14 days under same OLR: 2 kg VS/m³/d**

Linear regression analysis of the accumulative, absolute gas yield recorded per day was completed for each OLR and showed the rate of gas production was approximately in proportion to the increased loading of VS (Figure 4; Table 4).

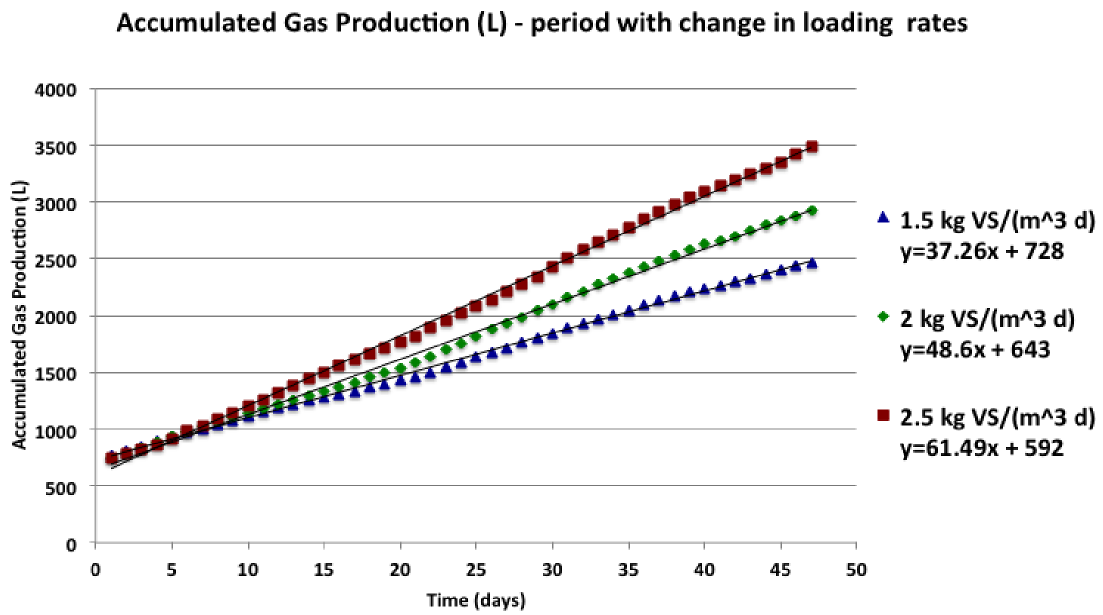


Figure 4: **Effect of OLR in sewage sludge on accumulative absolute biogas yield by mesophilic anaerobic digestion**

Table 4: **Regression analysis of accumulative biogas production from mesophilic anaerobic digestion at different sludge OLRs.**

Dig	OLR [b]	Regression Line	R^2	Rate Constant	% Change in rate constant [a]	Accum. Gas (L) Second period	% Change in accumulated gas [a]
1	1.5	y = 37.26x + 728	0.998	37.3	-	1718	-
2	2	y = 48.6x + 643	0.996	48.6	30.4	2176	26.2
3	2.5	y = 61.47x + 592	0.998	61.5	65.0	2735	59.3

a: % change from digester 1.
b: Target Load in kg VS/(m^3 d).

Specific gas yield

Table 5 shows the gas yield per tonne of VS and DS fed and per kg of VSD. Specific gas production increased in linear response to organic loading rate and improved by 17 % from 453 m^3/t VS to 529 m^3/t VS at the lowest (1.5 kg VS/m^3/d) and highest rates (2.5 kg VS/m^3/d) fed, respectively. However the data had a relatively high variance. Possible reasons for the variability were (a) the inherent variability in data derived from sewage sludge, (b) VS loadings were not precisely controlled at the target levels, (c) loading rates were based on DS and not directly on VS and (d) the variability in the daily specific gas yield recorded may have been affected by an artefact of the experimental apparatus. Nevertheless, linear regression analysis showed there was a highly statistically significant relationship between gas yield and VS and DS feeding rate (*P*<0.001), and the effect of OLR on gas production per kg of VSD was significant at *P*=0.02.

Table 5: **Specific gas yield**

	Actual OLR (VS/m³/d)	**Average and SD.**	**Min.**	**Max.**
m³/tVS fed	1.534±0.12	456 ± 63	332	667
	1.968±0.22	461 ± 66	346	665
	2.38±0.16	518 ± 81	248	667
m³/tDS fed	1.534±0.12	371± 51	255	516
	1.968±0.22	370 ± 54	265	513
	2.38±0.16	389 ± 66	191	517
m³/kg VSD	1.534±0.12	1.13 ± 0.16	0.77	1.48
	1.968±0.22	1.06 ± 0.17	0.82	1.47
	2.38±0.16	1.18 ± 0.2	0.58	1.61

Figure 6 shows the relationship between specific gas yield relative to the OLR.

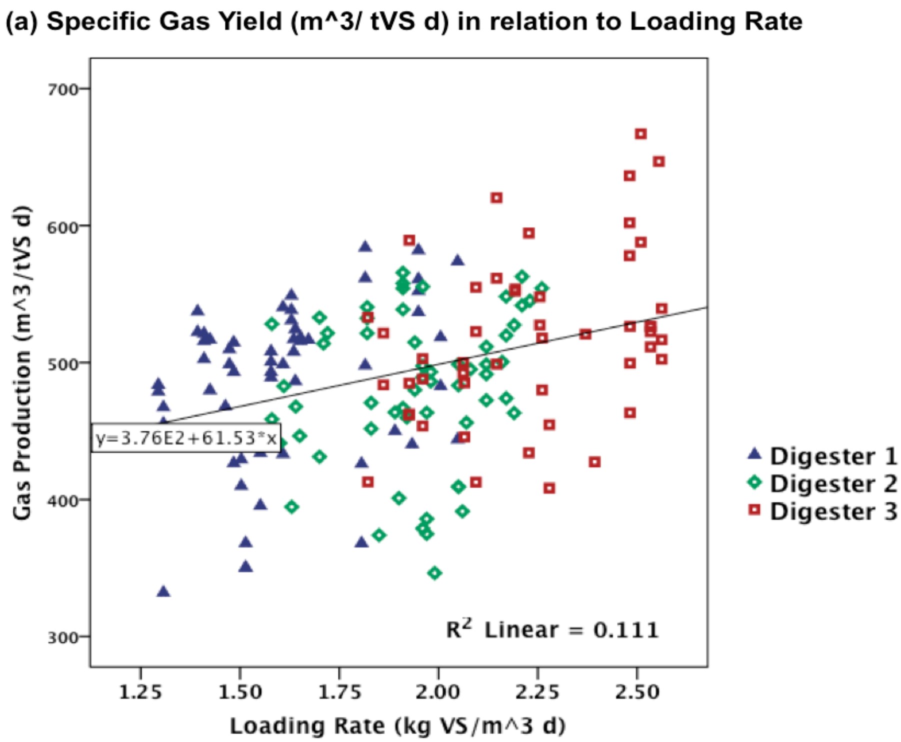


Figure 5: **Regression analysis of specific gas yield per tonne of VS fed in relation to OLR. Calculations of gas yield based on daily values of accumulative gas production.**

Gas composition

The gas composition did not vary significantly as a result of load changes. The average gas composition was 37.6±0.45% for CO_2 and 64.5±0.52% for CH_4 (Table 6).

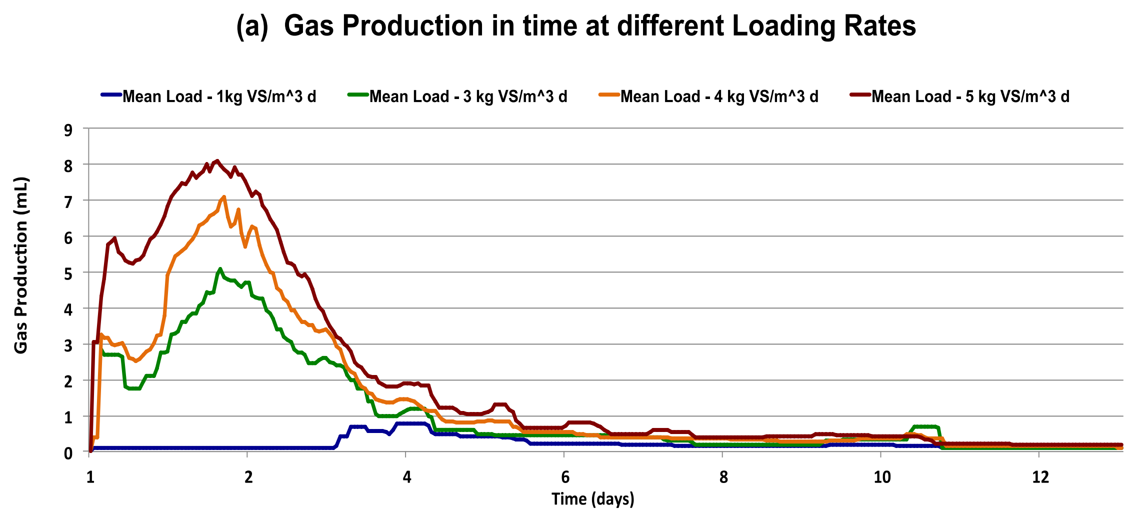
Table 6: **CO_2 and CH_4 yield for different OLRs.**

	CO_2 (%)			CH_4 (%)		
OLR (VS/m³/d)	**1.5**	**2**	**2.5**	**1.5**	**2**	**2.5**
Mean	37.97	37.62	37.07	64.94	63.95	64.72
Max.	39.75	39.01	39.58	67.51	66.35	67.76
Min.	36.55	37.16	35.66	62.64	61.94	61.99
SD	0.90	0.51	1.07	1.59	1.42	1.91

Laboratory Scale Batch Reactors

Gas Production

Figure 6 shows the gas production per hour and the accumulative gas production. Absolute gas production, measured in ml of CH_4, increased with the increase in OLR. An initial peak followed by a decrease in CH_4 production was visible on the first day. Figure 6a indicated that, in a batch process, the majority of the gas was produced within the first 3 days of digestion. This is common to all triplicates with OLRs of 3, 4, and 5 kg VS/m3/d. Gas production was only detected from day 3 for the 1.0 kg VS/m3/d OLR.



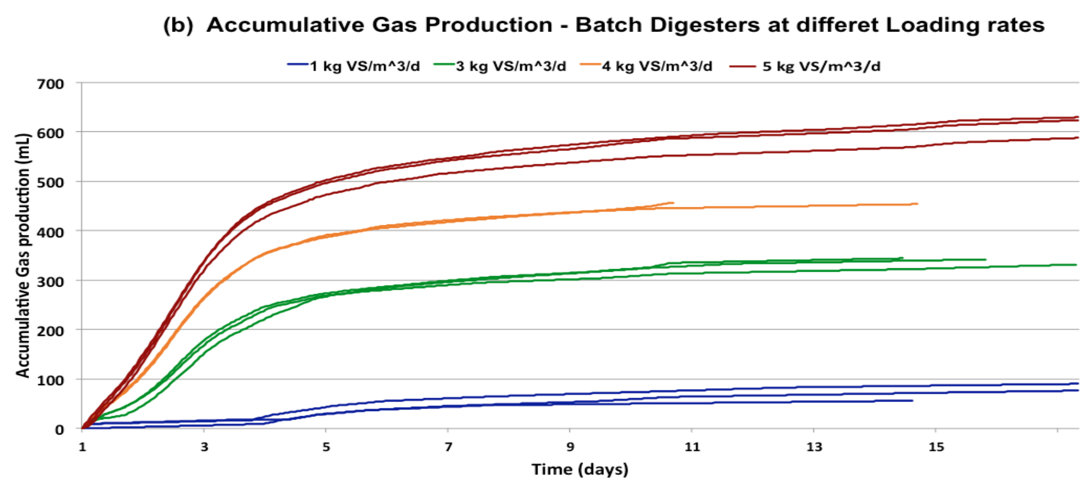


Figure 6: Absolute gas production (a) per day, and (b) accumulative in time.

Figure 7 shows the mean accumulative gas yield in m^3 CH_4 per tonne of VS.

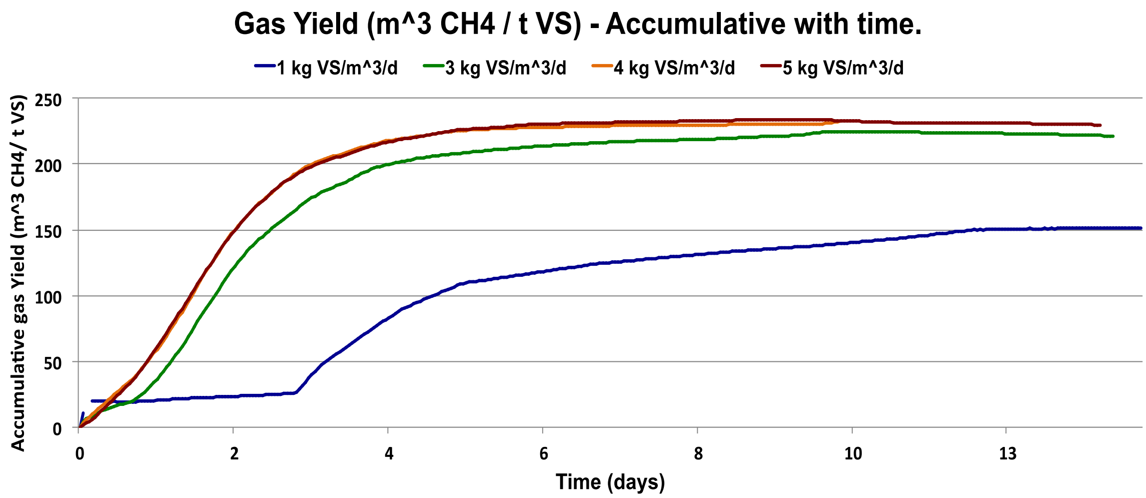


Figure 7: **Effect of OLR on accumulative specific methane yield (m^3 CH_4/tVS) in relation to time for mesophilic batch digestion of sewage sludge.**

Gas yield increased from 3 to 4 kg VS/m^3/d however a further increase of 1 kg/m^3/d did not show higher efficiency.

Model fitting

Table 7 summarises the results from the modelling of specific gas production from mesophilic digestion of sewage sludge at different OLRs applied to the batch digestion test. Both models provided reasonable approximations of gas specific gas accumulation with R^2 values >96%. However, visual inspection suggested that the logistic model more closely represented the gas production profile. The rate constants of the exponential and logistic models increased by 18.9% and 19.4%, respectively, by increasing the OLR from 3 to 4 kg VS/m^3/d. However, increasing the OLR from 4 to 5 kg VS/m^3/d only had a small effect and, in this case, the difference in the rate constants only increased by 2.4% for the exponential model, and 5.5 % for the logistic model. Figure 8 shows an example of the model fitting.

Table 7: **Summary of exponential and logistic model statistics of accumulative biomethane gas yield in relation to OLR of sewage sludge in batch mesophilic digestion tests**

Exponential Model

Load (kg VS/m³/d)	Maximum yield (N_{max})	Rate constant (k)	R^2	RMSE
3	179.0	**0.387**	0.96	10.21
4	187.6	**0.46**	0.97	9.618
5	192.6	**0.471**	0.97	8.4

Logistic Model

Load (kg VS/m³/d)	Maximum yield (N_{max})	Rate constant (k)	R^2	RMSE[a]
3	171.1	**1.271**	0.99	5.61
4	178	**1.517**	0.996	3.417
5	186.9	**1.434**	0.99	2.516

a: Root Mean Square Error (RMSE)

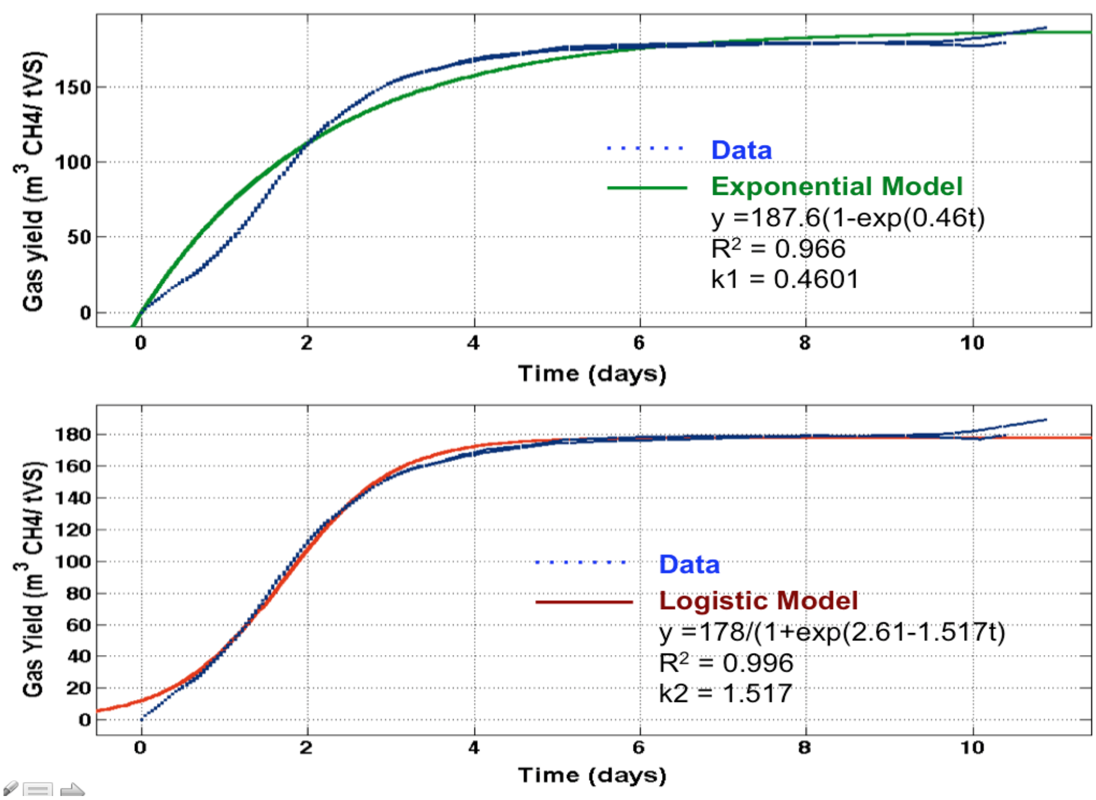


Figure 8: **Example of model fitting - exponential and logistic models of accumulative gas yield from mesophilic anaerobic digestion of sewage sludge for an OLR of 4 kg VS/m³/d.**

Conclusions

- The different OLRs applied during the experiment did not affect the stability or performance of the digesters, and digester pH, alkalinity and VFA were maintained at acceptable levels.
- Absolute gas production increased significantly with increasing OLR. Rate constants found for the accumulative gas production showed an increase of 59.3% from 1.5 VS/m^3/d to 2.5 kg VS/m^3/d.
- Specific gas production increased in linear response to organic loading rate and improved by 17 % from 453 m^3/t VS to 529 m^3/t VS at the lowest (1.5 kg VS/m^3/d) and highest rates (2.5 kg VS/m^3/d) fed, respectively. However the data had a relatively high variance.
- Numerical modelling of the specific gas production results obtained from the batch digestion tests also showed that gas yield improved with increasing OLR from 1.0 to 4.0 kg VS/m^3/d. However, no further improvement in specific biogas production was observed by raising the OLR from 4 to 5 kg/m^3/d.

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