THERMOPHILIC ANAEROBIC DIGESTION OF WINERY WASTE (VINASSES): KINETICS AND PROCESS OPTIMIZATION

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SYNOPSIS

Vinasses from wine-distilleries has a high organic contaminant load (16–25 g COD l^{-1}) an acidic character (pH about 3.8), and are discharged at almost 90°C.

For this reason, this paper examines the viability of the thermophilic anaerobic process as an alternative to mesophilic process for the reduction of waste strength.

Start-up and acclimatisation of the digesters until attainment of steady-state conditions, and kinetic studies for the thermophilic anaerobic process to achieve an optimum purifying performance were realized.

Substrate utilization and methane production models, both proposed by Chen and Hashimoto, predicted accurately the performance of the process and may be used in the design of treatment units.

Once optimum operating conditions had been attained (at four days retention time and 4.25 kg COD m^{-3} day^{-1} load density) COD removal of 88% and 0.25 m^3CH_4 kg^{-1}COD added were achieved.

Introduction

The crisis affecting distilleries as a consequence of their high energy consumption in the distilling process is being further exacerbated by the need to treat the waste, and the high cost which this normally involves.

Biological waste treatment methods are best for these residues whose feature is their essentially high organic contaminant load.

Anaerobic digestion may be seen as a viable alternative for reducing the contaminating factor of these industries waste products while at the same time producing a biogas[1–4] with methane content between 60–80%, which could eventually cover a large part of their energy needs.[5–9]

A particularly important factor in this treatment is operating temperature which determines the preponderant bacterial flora and growth rate. There are three temperature ranges within which the process can take place.

	Optimum temperature
(a) cryophilic:	15°C
(b) mesophilic:	35°C
(c) thermophilic:	55°C

The mesophilic range is traditionally used since it is generally thought that maintaining a high temperature is financially disadvantageous whilst degradation within the cryophilic range is too slow. However, the thermophilic range has now begun to merit consideration because reaction rates there are considerably higher than in the mesophilic and cryophilic ranges,[12,13] and thus the retention time necessary to reduce a given contaminant load by a certain percentage is shorter.

This is practicable in cases like wine distilleries, where the waste is discharged at almost 90°C,[14,15] thus considerably lowering the costs of maintaining the system at 55°C.

This paper studies the applicability of the thermophilic anaerobic process to vinasses from wine distilleries and the subsequent establishment of optimum operating conditions for adequate purification performance.

Kinetic Models

The experimental results of anaerobic wine-vinasses digestion are compared with theoretical results predicted from two kinetic models of biological treatment fitted to high organic strength wastes. These models are the Substrate Utilization Model and the Methane Production Model, proposed by Chen and Hashimoto.[16,17]

Substrate utilization model:

The main characteristics of the Substrate Utilization Model are:

(*a*): The specific growth rate of micro-organisms, μ, is defined by the Contois' equation:[16]

$$\mu = (\mu_{\max} \cdot |S|)/(\beta \cdot |M| + |S|) \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where $|M|$ is the cell mass concentration, $\mu_{\max}$ is the maximum specific growth rate of micro-organisms, $|S|$ is the biodegradable effluent substrate concentration, and β is a kinetic parameter;

(*b*): Continuous or semicontinuous completely mixed flow systems without solids recirculation are used;

(*c*): The predominant micro-organisms in the biological treatment system are not present in the influent;

(*d*): It is assumed that the maintenance energy per unit of cell mass is small, resulting in a constant growth yield coefficient, Y, (ratio of cell mass concentration to substrate concentration);

(*e*): Cellular lysis is not taken into account.

According to this model, since $\mu = 1/\theta$ for continuous process, the Contois' kinetic equation can be expressed as:

$$\theta = 1/\mu_{\max} + K/\mu_{\max} \cdot [(|S|_0 - |S|)/|S|]. \quad . \quad . \quad . \quad (2)$$

where θ is the hydraulic retention time, $|S|_0$ is the biodegradable substrate concentration in the feed, and K is a dimensionless kinetic parameter equal to $Y \times \beta$. Substrate concentration can be expressed either as COD or DVS.

Methane production model.

Given that the reduction in the contaminant load of the effluent must be in proportion to methane production, the following expressions are obtained for the methane production model:[17]

$$B/(B_0 - B) = (\mu_{\max}/K') \cdot \theta - 1/K' \quad . \quad . \quad . \quad (5)$$

$$\theta = 1/\mu_{\max} + K'/\mu_{\max} \cdot [B/(B_0 - B)] \quad . \quad . \quad . \quad (6)$$

where:

B = the number of litres of methane produced at STP per gram of organic matter added to the digester.

B_0 = the number of litres of methane produced at STP per gram of organic matter added to the digester for an infinite retention time.

θ = the retention time.

$\mu_{\max}$ = the maximum specific growth rate of the micro-organisms.

K = a dimensionless kinetic parameter.

Table 1: Characteristics of Influents Used during Start-up, Acclimatization, and Kinetic Studies.

		Vinasses						
Parameter	**Cow-dung**	A	B	C	D	E	F	G
pH	7.06	3.85	3.80	3.56	3.82	3.78	3.75	3.56
COD (g O_2 l^{-1})	7.78	32.16	17.55	13.03	16.25	16.61	16.97	17.73
BO_5D (g O_2 l^{-1})	3.13	18.11	13.51	7.47	11.29	11.66	12.03	11.41
TS (g l^{-1})	8.66	31.55	18.13	13.25	18.90	18.46	18.03	17.64
VS (g l^{-1})	6.40	21.70	13.97	8.44	13.13	12.96	12.78	11.44
SS (g l^{-1})	4.07	1.88	0.70	0.78	0.51	0.70	0.89	0.98
VSS (g l^{-1})	2.90	1.62	0.66	0.66	0.48	0.61	0.73	0.52
TKN (g N l^{-1})	0.510	0.273	0.376	0.152	0.265	0.304	0.342	0.267
PO_4^{3-} (g P_2O_5 l^{-1})	0.240	0.120	0.063	0.039	0.131	0.120	0.110	0.201
PF (g gallic acid l^{-1})		0.964	0.607	0.367	0.380	0.406	0.432	0.851

The parameter B_0 is obtained by means of the equation:

$$B = B_0[1 - K'/(\theta/\theta_{min} - 1 + K')]. \quad . \quad . \quad . \quad (7)$$

applied to the case where $\theta/\theta_{min} > 1 - K'$.

θ_{min} is the minimum retention time:

$$\theta_{min} = 1/\mu_{max}.$$

Materials and Methods

Equipment

Completely mixed semi-continuous flow digestors without sludge recirculation were used. Hydraulic retention time (HRT) coincides with solids retention time (SRT), in this type of digester. Their capacity was two litres with a working volume of 1.8 litre. They were equipped with gas and effluent outlets and feed inlets.

The digesters were maintained at 55±1°C by immersion in thermostatic baths.

Analytical methods

The following parameters were analysed:

(a): In liquid samples:

Biochemical oxygen demand (BO_5D); chemical oxygen demand (COD); pH; total solids (TS); volatile solids (VS); solids in suspension (SS); volatile solids in suspension (VSS); volatile acidity (VA); total Kjeldahl nitrogen (TKN); phosphates (PO_4^{3-}); polyphenol index (PP); and alkalinity (Alk).

Analyses were carried out according to Standard Methods,[18] except for the polyphenol index which was determined by the Folin-Ciocalteu reactive method.[19]

(b): In gaseous samples:

% carbon dioxide (%CO_2); % hydrogen (%H_2); and % methane (%CH_4).

The analyses were carried out with an Orsat analyser based on volumetric and combustion processes.

All experiments were conducted in duplicate.

pH, produced volume of biogas, and biogas composition were daily analysed in all the cases.

In start-up and acclimatisation studies, the characterization parameters of the effluents were analysed twice weekly.

In kinetic studies stage, hydraulic retention time was maintained for three weeks to assure steady-state conditions. Last week, samples of effluents were taken off and analysed, first untreated then later after centrifuging at 1000 g for five minutes.

Experimental procedures

START-UP

As wine-vinasses lack the micro-organisms necessary to carry on the anaerobic digestion process, bacterial flora were obtained from cow-dung with subsequent acclimatisation to wine-vinasses.

The methodology followed for starting up the process was as followed:

The cow-dung was mixed with distilled water to produce a suspension of an approximate concentration of seven grams of volatile solids per litre. The digesters were filled with 450 ml of the prepared suspension and 1350 ml of distilled water. After this, the digesters received a daily feed of 90 ml of cow-dung suspension, while the same volume was drained off. This feed-rate was maintained for six weeks, the time necessary to attain a steady production of biogas with methane content between 60–70%. In the last week, 0.4 g of glucose per day was added to the feed.

ACCLIMATISATION

On successive days during the period of acclimatisation of the bacterial flora to the wine-vinasses, 200 ml of vinasses, previously neutralized with sodium carbonate, were added daily to the digesters. The pH (7–8) was maintained by adding 7N NaOH to the digester. This period of acclimatisation was maintained until a steady production of combustible biogas was attained, containing about 60–70% methane.

KINETIC STUDIES

Semicontinuous.

In order to achieve optimum purification, a series of experiments was conducted at different retention times (the solids retention time, SRT, coincides with the hydraulic retention time, HRT, in this type of digester).

The optimization study was carried out in duplicate, and hydraulic retention times of 20, 12, 10, 8, 7, 6, 5, 4, 3, and 2 days were tried.

During these experiments samples of effluent were collected and analysed in order to ensure that steady state conditions had been attained.

The experimental results for anaerobic wine-vinasses digestion are compared with theoretical results predicted from two kinetic models of biological treatment fitted to high organic strength wastes. These models are the Substrate Utilization Model and Methane Production Model, proposed by Chen and Hashmoto.[16,17]

Batch

Not all the organic matter in a given waste can be used up by the micro-organisms, since part of it is difficult to break down.

Some authors[20,21] suggest that in the case of wine-vinasses this proportion of biodegradation-resistant organic matter is composed basically of polyphenol-like compounds.

In order to apply the kinetic models of Chen and Hashimoto it is necessary to know the amount of non-biodegradable organic matter contained in the waste.

For this purpose, a discontinuous experiment was carried out. Vinasses were incubated inside the digester until the amount of gas produced was insignificant. From this time, incubation was continued for two more weeks, at the end of

Table 2: Characteristics of Gaseous and Liquid Effluents During Start-up and Acclimatization Stages. (Average values from four analyses.)

	Start-up						Acclimatization			
Week:	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
pH	7.35	7.12	7.43	7.39	7.28	7.00	7.30	7.50	7.40	7.35
COD (g O_2 l^{-1})	3.96	3.03	3.58	3.27	4.22	4.49	7.80	7.49	8.37	9.08
TS (g l^{-1})	4.82	3.46	3.79	4.17	4.90	5.38	11.64	12.54	15.13	17.24
VS (g l^{-1})	3.08	2.40	2.59	2.86	3.26	3.56	5.71	6.33	7.52	8.61
SS (g l^{-1})	1.43	1.34	1.66	1.71	2.06	2.04	2.26	2.24	2.13	2.08
VSS (g l^{-1})	0.75	0.99	1.21	1.18	1.36	1.36	1.42	1.47	1.42	1.39
TKN (g N l^{-1})	0.28	0.21	0.27	0.28	0.28	0.29	0.40	0.39	0.44	0.46
Alk (g CO_3Ca l^{-1})	1.17	0.93	1.36	1.44	1.61	1.89	4.94	6.12	7.18	8.37
VA (g HAc l^{-1})	0.11	0.31	0.25	0.21	0.26	0.44	1.55	1.27	2.23	2.32
Vol. gas (l day^{-1})	0.011	0.079	0.260	0.191	0.060	0.120	1.900	3.140	2.370	3.000
CO_2 (% vol)	—	4.9	5.7	8.0	6.1	30.0	39.4	33.5	39.5	30.0
H_2 (% vol)	—	n.d.*	n.d.*	n.d.*	n.d.*	n.d.*	1.8	1.7	1.5	1.6
CH_4 (% vol)	—	20.0	34.5	56.3	64.0	61.1	52.4	56.5	50.7	59.6

* n.d. = *not detectable with the analysis method used.*

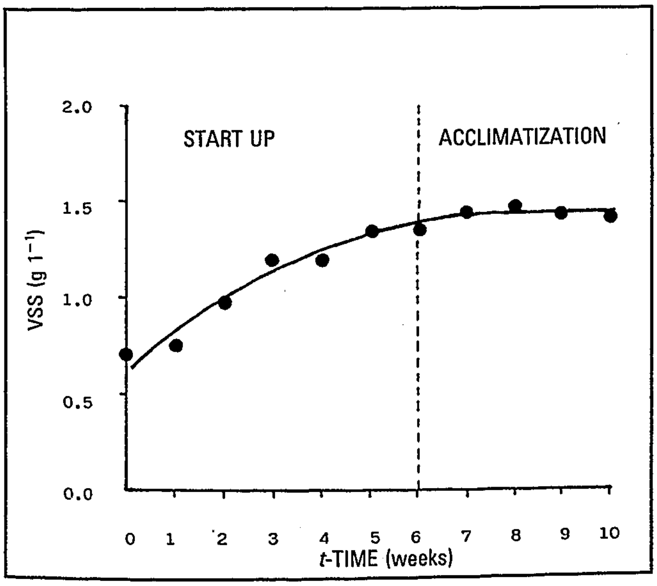

Figure 1: Volatile solids in suspension in the effluents through start-up of the system and acclimatisation of the bacterial flora.

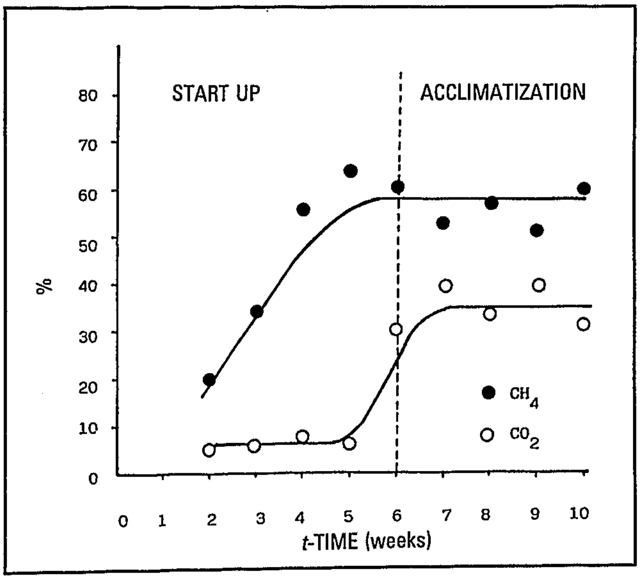

Figure 2: Percentages of methane and carbon dioxide in the biogas during start-up of the system and acclimatisation of the bacterial flora.

which analyses were made of the parameters quantifying organic matter (COD or VS). These values correspond to the level of non-biodegradable organic matter.

Results

The most significant results of the various stages are reported below.

Start-up and acclimatisation stages

Table 1 shows the results obtained from analysis of the feed during the start-up of the digesters (cow-dung to obtain bacterial flora and vinasse A to acclimatise the bacterial flora to wine-vinasses).

The results obtained from analysis of the liquid and gas effluents produced during the start-up of the digesters are shown in Table 2.

Figure 1 shows the variation of volatile solids in suspension during the start-up of the digester and the acclimatisation of the bacterial flora to wine-vinasses.

Figure 2 shows the CH_4 and CO_2 percentages in the biogas during the start-up of the digester and the acclimatisation of the bacterial flora.

Kinetic studies

BATCH

To determine the proportions of organic matter resistant to the thermophilic anaerobic biological process, the vinasses were incubated until the quantity of gas produced was unnoticeable. Incubation then continued for a further two weeks, at the end of which the quantifying parameters for organic matter were determined, with the following results:

Total non-biodegradable COD:	2.12 gO_2 l^{-1}
Total non-biodegradable VS:	2.08 g l^{-1}
Non-biodegradable soluble COD:	1.08 gO_2 l^{-1}
Non-biodegradable DVS:	1.48 g l^{-1}

SEMI-CONTINUOUS

Table 1 shows the properties of the feeds used in this stage (vinasses B to G).

Table 3 shows the properties of the liquid and gaseous effluents for the various HRTs.

Figure 3 shows the percentage removal of COD (uncentrifuged and centrifuged samples) for the HRT used.

Figure 4 shows the percentage of CH_4 and CO_2 in the biogas.

Table 3: Characteristics of Gaseous and Liquid Effluents During Kinetic Studies. (Average values from four analyses.)

HRT (day):	**20**	**12**	**10**	**8**	**7**	**6**	**5**	**4**	**3**	**2**
pH	7.69	7.60	7.48	7.31	7.50	7.60	7.46	7.54	7.62	7.14
COD ($gO_2\ l^{-1}$)	4.02	4.18	3.31	3.59	4.13	3.62	4.53	4.24	4.58	10.61
TS ($g\ l^{-1}$)	10.52	10.23	9.80	9.39	9.59	9.65	11.45	11.25	10.06	16.15
VS ($g\ l^{-1}$)	4.07	4.51	4.37	4.48	3.60	3.34	4.26	4.32	3.85	7.80
SS ($g\ l^{-1}$)	2.22	1.87	1.53	0.93	1.19	1.48	1.35	1.73	1.80	0.25
VSS ($g\ l^{-1}$)	1.08	1.35	0.98	0.93	0.74	0.70	1.12	1.12	0.43	0.10
TKN ($gN\ l^{-1}$)	0.28	0.24	0.42	0.39	0.30	0.31	0.31	0.31	0.30	0.30
Alk ($g\ CO_3Ca\ l^{-1}$)	6.18	6.01	4.64	4.90	5.39	5.47	6.19	6.10	5.54	5.65
VA ($g\ HAc\ l^{-1}$)	0.32	0.43	0.73	1.02	1.16	0.54	1.95	1.50	1.51	3.78
COD soluble ($gO_2\ l^{-1}$)	1.94	2.97	2.13	2.51	2.53	2.22	3.17	2.86	3.33	9.37
DS ($g\ l^{-1}$)	8.30	8.36	8.27	8.46	8.40	8.17	10.10	9.91	8.26	15.90
DVS ($g\ l^{-1}$)	3.00	3.16	3.39	3.55	2.86	2.64	3.14	3.20	3.42	7.70
Vol. gas ($l\ day^{-1}$)	0.949	1.509	0.974	1.104	2.071	2.622	2.693	3.076	3.000	2.471
CO_2 (% vol)	23.0	27.2	28.9	30.9	30.7	28.6	31.8	30.1	32.1	47.0
H_2 (% vol)	1.5	1.4	1.6	1.7	1.8	1.6	1.8	1.5	2.1	3.0
CH_4 (% vol)	67.1	62.0	63.7	61.0	61.6	62.3	59.9	61.0	58.1	44.4
Type of feed	Vinasse B	Vin. B	Vin. C	Vin. C	Vin. D	Vin. D	Vin. E	Vin. E	Vin. F	Vin. G

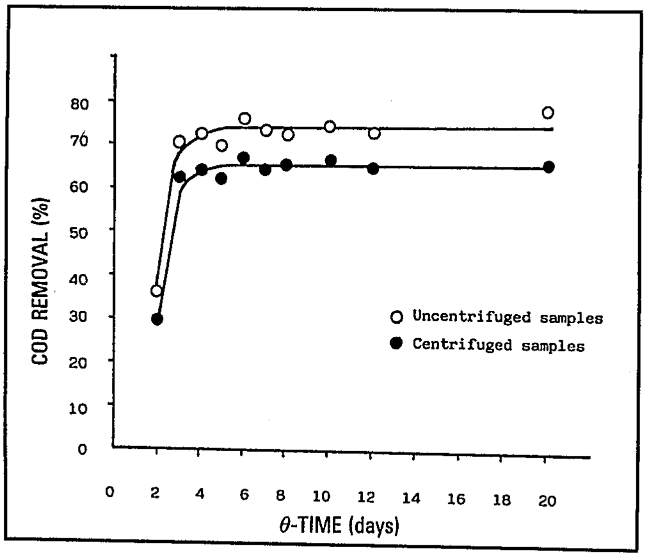

Figure 3: Percentage of COD removal *vs* hydraulic retention time in kinetic study period.

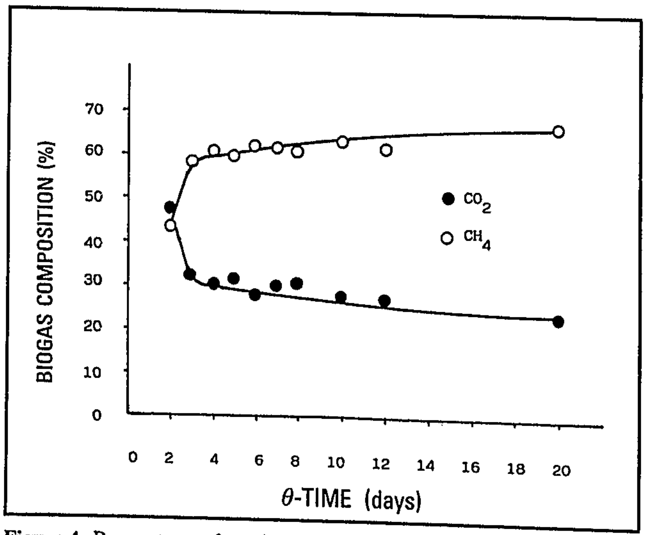

Figure 4: Percentage of methane and carbon dioxide in the biogas *vs* hydraulic retention time in kinetic study period.

Figure 5 plots hydraulic retention time *vs* the ratio of non biodegradable substrate concentration, expressed as COD or DVS for the obtention of the kinetic parameters of Substrate Utilization Model.

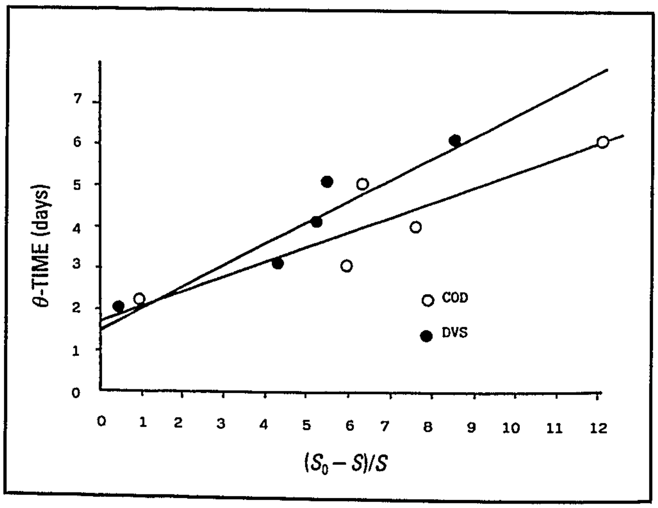

Figure 5: Hydraulic retention time *vs* the ratio $(S_0 - S)/S$, (O = COD and ● = DVS) in kinetic study period.

From Figure 5 the following kinetic parameters are obtained:

	COD	*DVS*
μ_{max}	0.608	0.647
K	0.214	0.329

Figure 6 shows the experimental percentage removal of COD together with the values forecast from the substrate utilization model (continuous line).

Figure 7 plots the litres of methane produced at STP per gram of organic matter added to the digester *vs* the inverse of the hydraulic retention time.

Figure 8 plots the hydraulic retention time *vs* the ratio $B/(B_0 - B)$ to give the kinetic parameters of Methane Production Model.

From Figures 7 and 8 the following kinetic parameters are obtained:

Parameter	**Organic matter referred to:**	
	COD	*DVS*
μ_{max}	0.586	0.583
K'	1.5456	0.9852
B_0	0.563	0.667

Figure 9, chosen as an example, shows the volume of methane produced per gram of VS added to the digester together with the forecast for the methane-production model (continuous line).

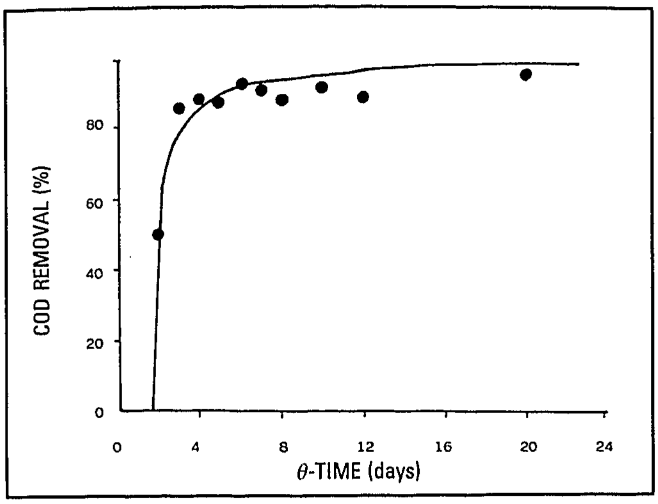

Figure 6: Experimental values of percentage of COD biodegradable removal *vs* hydraulic retention time in kinetic study period. Continuous line denotes the theoretical curve obtained from the substrate utilization model.

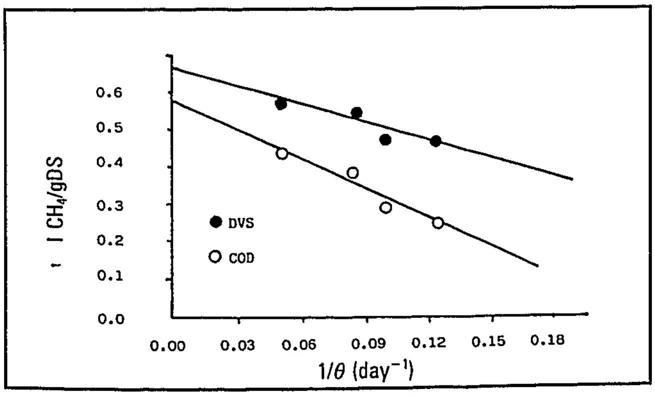

Figure 7: Litres of methane produced at STP per gram of organic matter added to digester, expressed as (O) COD and (■) DVS, *vs* inverse of hydraulic retention time in kinetic study period.

Discussion

Figure 1 shows a continuous increase in volatile solids in suspension during the start-up weeks.

Figure 2 shows a continuous increase in methane percentage during the first five weeks in a similar way to the suspended volatile solids curve (Figure 1). This increase in CH_4 occurred because, since the bacterial flora was growing, the production of CH_4 and CO_2 was not dependant on the density of the feed, but on the number of micro-organisms present in the medium. The CO_2 percentage, however, remains practically constant during the start-up period because the amount produced is very small and most of it is used to increase the CO_3^{2-}/CO_3H^- buffer.

During fourth and fifth weeks, the volume of biogas per day decreased, as seen in Table 2. A possible reason for this is low organic matter concentration or the presence of an inhibitor.

In order to determine which was correct, 0.4 g of glucose (an easy substrate to degrade and without an inhibitor effect on the micro-organisms) was added to the cow-dung each day during the sixth week. This effected an increase in the quantity of biogas produced, the carbon dioxide percentage and the volatile fatty acids. Thus it is concluded that the biogas volume decrease was due to a low organic concentration in the cow-dung.

From the sixth week, coinciding with the change in feeding, a considerable rise in CO_2 percentage in the biogas was observed. This is then stabilized during the flora adaptation to wine-vinasses.

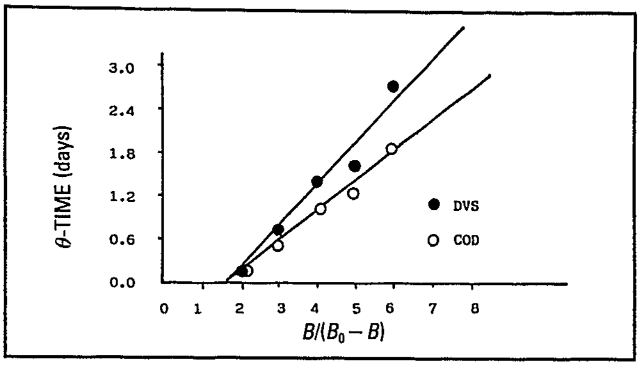

Figure 8: Hydraulic retention time *vs* the ratio $B/(B_0-B)$, (O = COD and ● = DVS) in kinetic study period.

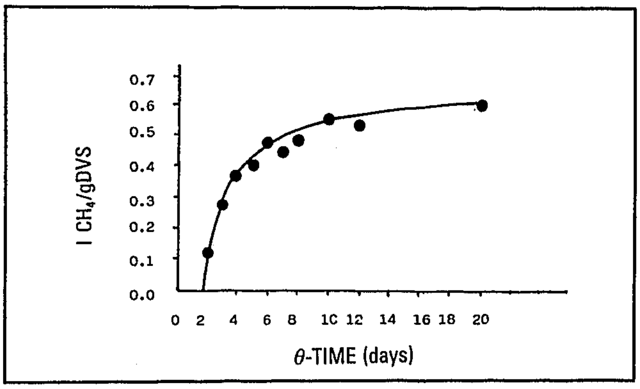

Figure 9: Experimental values of litres of methane produced at STP per gram of DVS added to digester *vs* hydraulic retention time in kinetic study period. Continuous line denotes the theoretical curve obtained from the methane production model.

Acclimatisation

The sharp rise in the amount of total solids and alkalinity values observed at the seventh week was due to the digesters being fed with vinasses neutralized with Na_2CO_3. Because of this, the levels of mineral solids and CO_3^{2-}/CO_3H^- buffer increased in the digesters. The values of COD, VS and VA also increased since the organic content of the vinasses is higher than cow-dung. Equally, a high increase in the volume of gas produced could be observed.

Figures 1 and 2 show, respectively, that both the volatile solids in suspension and the biogas composition (%CO_2 and %CH_4) were stabilized in this stage.

Kinetic studies

Since the vinasses could not be stored for long periods of time, different samples labelled B to G were taken consecutively from the distillery output. This apparently had no significant effect on the overall shape of the curves (Figures 3 to 9) and, therefore on the kinetics, although it may account for the fluctuation in the results which is particularly apparent in Figures 3, 4, 6, and 9.

All the parameters behave similarly for retention times between 20 and 3 days, while there is a clear difference in the two-day HRT. The explanation for this is that the two-day HRT must be close to the minimum retention time for the system being used; in other words, it must be close to that HRT at which the bacteria are washed out more quickly than they can regenerate.

Thus, as shown in Figures 3 and 4, the percentage removal of COD and percentage of methane in the biogas fall sharply for the two-day HRT, while volatile acidity (see Table 3) and percentage of carbon dioxide in the biogas increase considerably. This phenomenon is understandable, since the methanogenic flora, the slowest to reproduce, do not have sufficient time to regenerate and the main activity is that of the acidogenic flora. As a result of this, the degradation of organic matter goes no farther than intermediate products

(CO_2, volatile fatty acids and H_2), stopping short of the final products (CH_4 and CO_2).

It seems, furthermore, that in the operating conditions tested, four days is the optimum HRT, given that it combines a high percentage of organic matter removal with the greatest daily volume of gas, a high ratio of volume of biogas produced at STP per gram of COD added to the system and 61% methane content. In addition, it is a short enough time so that the digester need not be over-large.

SUBSTRATE UTILIZATION MODEL

It can be observed that the values of μ_{max} are fairly close in both cases. K is, of course, dependent on the form in which the substrate concentration is expressed.

There is also a correlation, obtained by Chen and Hashimoto from experimental data[22] which makes it possible to calculate the value of μ_{max} as a function of operating temperature:

$$\mu_{max} = 0.013\,T - 0.129 \quad . \;. \;. \;. \;. \quad (3)$$

where T is the temperature (°C).

From which we obtain a value of $\mu_{max} = 0.586$ at 55°C, which is close to the experimental values. From the μ_{max} value, the minimum retention time, θ_{min}, may be obtained by applying the equation:

$$\theta_{min} = 1/\mu_{max}. \quad . \;. \;. \;. \;. \;. \quad (4)$$

giving an average θ_{min} value of 1.59 days.

This value of θ_{min} explains why the two-day experimental retention time shows marked instability.

METHANE PRODUCTION MODEL

The μ_{max} values obtained are very similar to those found by applying the substrate utilization model.

From the average value of μ_{max}, the minimum retention time is 1.71 days.

Conclusions

On the basis of the foregoing discussion, for the digesters and vinasses used, the following conclusions can be made:

(*1*): Thermophilic anaerobic fermentation is very adequate for wine-vinasses. It gives both an acceptable reduction in the contamination-indicator parameter and in the gas production, similar to those found by other authors[14] for the same substrate in the mesophilic range, but with substantially shorter HRTs.

(*2*): The percentage removal of biodegradable COD falls slightly from HRT = 20 (95%) to HRT = 3 (86%), then there is a sharp fall to HRT = 2 (50%). Similar variation for the rest of the parameters quantifying organic matter are observed.

(*3*): Percentages of methane in the biogas fall similarly from HRT = 20 (67%; 0.4 litres CH_4 at STP/gram of COD) to HRT = 3 (58%; 0.17 litres) with the same sharp fall to HRT = 2 (44%; 0.071 litres). At this HRT = 2 days the percentage of CO_2 in the biogas rises to 47%.

(*4*): Optimum retention time for anaerobic treatment of vinasses is around four days. With this time the effluent shows:

pH = 7.54;
COD removals = 88%;
volatile acidity = 1.5 grams expressed in grams of acetic acid per litre of sample;
alkalinity = 6.1 grams expressed in grams of calcium carbonate per litre of sample;
litres of methane at STP per gram of COD added to the digester = 0.25 l.

(*5*): The kinetic models proposed by Chen and Hashimoto are shown to be suitable for forecasting the system's working. The maximum specific growth rate, μ_{max}, calculated by means of these models is 0.606 day^{-1}, so a minimum retention time of 1.65 days is obtained, which agrees with the experimental minimum retention time of two days.

Symbols Used

Alk = alkalinity (mass/volume).
B = litres of methane produced at STP per gram of organic matter added to the digester (volume/mass).
B_0 = litres of methane produced at STP per gram of organic matter added to the digester for an infinite retention time (volume/mass).
BOD_5 = biological oxygen demand (mass/volume).
COD = chemical oxygen demand (mass/volume).
DVS = dissolved volatile solids concentration (mass/volume).
HRT = hydraulic retention time (time).
K = kinetic constant of substrate utilization model (dimensionless).
K' = kinetic constant of methane production model (dimensionless).
$|M|$ = cell mass concentration (mass/volume).
PP = polyphenol index (mass/volume).
$|S|$ = biodegradable effluent substrate concentration (mass/volume).
$|S|_0$ = biodegradable influent substrate concentration (mass/volume).
SRT = solids retention time (time).
SS = solids in suspension concentration (mass/volume).
TKN = total Kjeldahl nitrogen (mass/volume).
TS = total solids concentration (mass/volume).
VA = volatile acidity (mass/volume).
VS = volatile solids concentration (mass/volume).
VSS = volatile solids in suspension concentration (mass/volume).
Y = growth yield constant (cell mass/substrate mass).
β = kinetic constant of Contois' equation (dimensionless).
μ = specific growth rate of micro-organisms ($time^{-1}$).
μ_{max} = maximum specific growth rate of micro-organisms ($time^{-1}$).
θ = retention time (time).
θ_{min} = minimum retention time (time).

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