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SEMI-DRY ANAEROBIC DIGESTION OF MSW: INFLUENCE OF PROCESS PARAMETERS ON THE SUBSTRATE UTILIZATION MODEL

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ABSTRACT

In this paper the experiments carried out in a 3 m^3 reactor using mechanically sorted organic fractions of municipal solid waste as substrate are described. The influence of operating parameters such as hydraulic retention time (HRT), organic loading rate (OLR) and temperature are examined. Even at the critical levels of OLR and HRT used (6 days and 20 kg TVS/m^3d, respectively) the stability parameters have values which can be considered safe. A kinetic study is also carried out using the first order and step diffusional models, based on the biogas production profiles obtained after feeding the digester. The most relevant fact is the appearance of a "plateau" in these profiles. The larger the overload, the larger the plateau formed after feeding the digester. This approach could be used to control the digester stress.

KEYWORDS

Methanization; refuse; kinetic; overload; thermophilic.

INTRODUCTION

Anaerobic digestion is a biotechnology for the treatment of the organic fraction of municipal solid waste (OFMSW) which has gained increasing interest in the world (Cecchi et al, 1988, Cecchi and Mata-Alvarez, 1991). Work carried out over the past years on the pilot facilities existing at the University of Venice (Italy) using differently sorted OFMSW, in a wide range of different conditions, has demonstrated the feasibility of treating OFMSW at concentrations over 20% total solids (TS) and at hydraulic retention time (HRT) in the range of 6-8 days when a conventional stirred tank digester is operated under the thermophilic range of temperature (Cecchi et al., 1986; 1990; 1990a; 1991). These conditions - referred to here as semi-dry - allow the reduction of the digester volume and, consequently, the investment costs. Moreover, operation of the digester under thermophilic temperature results in improved yields (larger ultimate biogas yields) and kinetics. With these results it is clear that attention should be paid to such operation conditions because they represent a new positive factor to take into consideration when technologies for MSW treatment are compared.

Of the kinetic models presented in the literature, that proposed by the present authors and referred to as step-diffusional (SD) would appear to be especially appropriate to study the biodegradation of complex waste (Mata-Alvarez & Cecchi, 1989; Cecchi et al., 1990b). The main characteristic of the SD model is that it takes into account the composition of the substrate to predict the degradation rate profiles. The results obtained using this model with different substrates such as differently sorted OFMSW, primary and secondary sewage sludges (SS) and mixtures of SS and OFMSW separately collected have demonstrated this assumption (Cecchi et al., 1990c; Mata-Alvarez et al. 1990). On the other hand, when the first order model is applied, although it is simple and representative, the values of its constants vary with the substrate considered.

In this paper the results obtained under different thermophilic conditions working with mechanically selected OFMSW (MS-OFMSW) at the pilot plant mentioned above are examined, paying special attention to the aspects related with the kinetics of the process. Thus, the effect of different operating conditions such as temperature (ranging from 48 to 55°C), hydraulic retention time (6 to 8 days) and organic loading rate (OLR) from 13.5 to 20 kg TVS/m^3 d, on biogas production and other related yields are studied. These effects are also related to the observed kinetic constants of the first and step diffusional models.

MATERIALS AND METHODS

The digester was a 3 m^3 working volume conventional stirred tank reactor. The temperature was controlled within ± 0.5°C at the desired thermophilic value. The pressure of the gas inside the reactor was controlled to 180 - 200 mm water column (w.c.). The digester was fed twice a day with a substrate with around 20% TS content. The substrate used was the OFMSW from the plant of S.Giorgio di Nogaro (Udine, Italy). The sorting plant flow-sheet together with the most important characteristics of the OFMSW are reported elsewhere (Cecchi et al., 1990). The OFMSW was diluted from 75% TS to about 20% TS by using water and recycled liquid before feeding the digester, according to a recycle ratio (RR) defined as the recycle flow rate/total feed flow rate. The recycled liquid was obtained by filtration of the digester effluent through a gravity screen (mesh size = 1 mm).

The following composition parameters were monitored: TS, TVS, TCOD, TOC, STS, SVS, SCOD in the feed and in the digester, the biogas and the daily feed flow rates. The stability parameters pH, Total Alkalinity (TA), Volatile Fatty Acids (VFA) of the reactor sludge and the percentage of CO_2 in the biogas were also monitored. The gas production rate (GPR) - measured by a wet gas meter - was monitored and registered continuously by an acquisition data unit that also stored the continuous measurements of the CH_4 percentage in the biogas. This analysis was carried out by an infrared cell. Both the sludges fed and those inside the digester were analyzed every two days. The composition parameters were determined directly on the sample taken from the feed-stock tank and the reactor (TS, TVS) or on the dried matter at 105°C (TCOD, TOC) according to Standard Methods (1985); TA was determined on the supernatant of the sample (end points: pH = 3.8 and 6.0 for TA4 and TA6, respectively); VFA were determined by a gas-chromatographic method. Conditions of this analysis were: Column: Type Wide Bore (Nukol. i.d. 0.53 mm, length, 0.15 m), Injector temperature, 200°C; Detector - flame ionization - temperature, 200°C; Temperature program, Initial: 100°C; Step: 10°C/min; Final: 180°C; Air flow rate, 420 cm^3/min; H_2 flow rate, 33 cm^3/min; Carrier flow rate, 10 cm^3/min. Ammonia ($N\text{-}NH_{4)}$ was monitored as an indicator of the essential nutrient presence for bacterial growth (Glauser et al., 1987).

TABLE 1 Operating Conditions And Yields

	Ref	Per 1	Per 2	Per 3	Per 4
OPERATION CONDITIONS					
T Reactor (C)	54.8	54.6	51.5	47.8	48.1
HRT (d)	11.7	7.8	6.1	6.3	8.6
OLR (kgVSadded/ m^3 d)	6.9	13.5	19.9	18.5	14.4
FEED CHARACTERISTICS					
TS (g/kg)	164.2	224.6	210.6	199.8	216.9
TVS (g/kg)	81.0	105.8	121.4	120.4	123.7
STS (% TS)	8.8	7.6	6.9	8.1	8.7
SVS (% TVS)	10.4	9.7	6.1	6.9	9.4
TCOD (g/kg)	128.6	115.0	159.1	140.9	134.5
SCOD (g/kg)	12.5	14.7	10.9	15.3	13.0
TC (% TS)	20.1	24.0	29.5	30.2	27.5
VFA (mg HAc/l)	6038	7860	2712	364	3213
pH (-)	6.41	7.17	6.93	704	7.28
TA(6) (g $CaCO_3$/l)	0.3	0.8	0.8	1.4	0.9
TA(4) (g $CaCO_3$/l)	4.5	3.8	5.3	6.9	4.7
REACTOR CHARACTERISTICS					
TS (g/kg)	93.5	173.3	179.1	178.8	186.8
TVS (g/kg)	55.1	76.1	87.1	90.5	90.3
STS (% TS)	8.6	6.0	7.0	7.6	6.4
SVS (% TVS)	8.4	7.6	7.4	6.9	7.4
TCOD (g/kg)	38.7	87.0	121.1	104.1	117.2
SCOD (g/kg)	2.9	5.5	46.1	6.4	5.0
TC (% TS)	21	23.8	29.4	28.5	25.1
C2 (mg HAc/l)	384	614	750	373	374
C3 (mg HAc/l)	106	52	1260	48	28
i-C4 (mg HAc/l)	34	1	33	29	10
C4 (mg HAc/l)	1	13	11	0	6
i-C5 (mg HAc/l)	0	1	70	1	2
C5 (mg HAc/l)	0	13	27	0	1
VFA (mg HAc/l)	525	694	2151	451	421
pH (-)	7.17	7.24	7.17	7.30	7.25
TA(6) (g $CaCO_3$/l)	2.4	3.0	2.4	3.6	3.2
TA(4) (g $CaCO_3$/l)	5.0	6.9	7.6	9.0	7.9
TA4-TA6 (g $CaCO_3$/l)		3.9	5.2	5.5	4.7
NH_4-N (g/l)	217.6	199.6	82.3	109.2	25.0
DIGESTER YIELDS					
GPR (m^3/m^3 d)	2.8	4.1	4.7	4.0	3.5
SGP (m^3/kgVSadded)	0.41	0.30	0.23	0.24	0.29
CH_4 (%)	62	53	57	61	62.6
C rem. (%)	47	33	25	23	30
TVS rem. (%)	43	37	27	26	32
TCOD rem. (%)	40	35	29	27	35
f_B (%)	94.2	58.9	48.6	54.2	67.2
f_G (%)	93.2	68.2	52.3	54.6	65.9

RESULTS AND DISCUSSION

Four periods of steady digester performance are considered in this study. The operating conditions used in the four periods, shown in Table 1, were quite extreme both for the high organic loading rates and low HRT. Table 1 shows also a reference period in which the digester was operated with the same substrate at a thermophilic temperature (Cecchi et al. 1991). At the reference conditions, estimated ultimate biogas and methane yield, G_0 and B_0, are around 0.44 and 0.27 m^3 , biogas and CH_4/kg VS respectively (Cecchi et al., 1991). Using these values, the percentages of biodegradation achieved,f_G and f_B, can be estimated by the ratio between the specific biogas (SGP) and methane production and the ultimate yields (Mata- Alvarez et al., 1990a). The resulting values vary between 52-68% and 49-67% for the periods studied, when values around 95% can be obtained using lower OLR (around 7 kg TVS/m^3 d), (see reference period). Table 1 reflects the values of f_G and f_B for all the stationary states considered.

As can be seen from the data in Table 1, the digester performance was quite satisfactory from the point of view of the gas production and stability. Even in period 2, at an OLR of 19.9 kg TVS/m^3 and HRT 6.1 days, pH was 7.2 and the VFA slightly exceeded a concentration of 2 g/l (although more than a half was propionic acid). This relatively high concentration of VFA is an indication of a digester overload. In fact, the specific gas production decreased substantially (as compared with other periods). In any case, these conditions could be considered within a possible operational range, although close to those of digester failure. From the practical point of view these conditions are far from the most economic, which are reported to be those of the reference period, when the comparison also included the period 1 (Cecchi et al, 1991).

To establish a comparison among the four periods, a reasonable approach could be to study them by establishing homogeneous couples, two at similar temperature and other two at similar OLR, the main operating parameters. Thus and as a first step, the effect of thermophilic temperature will be studied considering: a) periods 2 vs. 3, where the OLR and HRT are practically the same and temperature varies 3-4°C; b) periods 1 vs. 4, again with OLR and HRT having similar levels and temperature varying around 6.5°C. The second step will consider a match between periods 1 vs. 2 and 3 vs. 4, in order to study the effect of OLR and HRT variations.

Effect of temperature: Comparison of periods 2 vs. 3 and 1 vs. 4

If period 2 is matched with period 3, it appears that the level of VFA is the main difference between them. It seems reasonable to attribute this difference to the increase of temperature from 47.8 to 51.5°C. Thus, it is possible to assume that under the range of stressed conditions, a relatively small increase of temperature can produce an imbalance in the trophic chain and, consequently, an accumulation of VFA. A similar effect was also observed when source-sorted OFMSW was used: Within a small range of temperatures, an accumulation of VFA in the feed of the digester was produced, due to the fermentation of ethanol to acetic acid (Mata-Alvarez & Cecchi, 1989). This behaviour would be consistent with the finding that hydrolytic bacteria are strongly affected by temperature variations (Mata-Alvarez & Cecchi, 1989). It seems reasonable to assume that an accumulation of VFA can be produced by extreme values of any parameter although the parameter will normally be the OLR. In this case, however, the imbalance is produced by a rise in temperature. For instance, under mesophilic conditions, Cecchi et al (1986) found an overloading situation, similar to period 2, working with source-sorted OFMSW. At an OLR of 6.9 kg TVS/m^3 and HRT of 8.9 days, VFA concentration was 1650 mg/l (nearly the double of a non-overloaded period) and the yields decreased substantially (SGP decreased more than 30%).

Considering the digester performance, it should be noted that both SGP and f_G slightly decrease from period 3 to period 2. In contrast, an increase in GPR (from 4.0 to 4.7 m^3/m^3.d) is produced which could be assumed as an advantage. However, if f_B is considered and the methane content in biogas is taken into account, it can be observed that it decreased from 54.2 to 48.6 %. Consequently, the GPR increment can only be considered a partial advantage. In fact, the methane production rate went only from 2.45 to 2.68 m^{3}CH$_4$/m^3.d (8.5 % higher). This behaviour, together with the VFA accumulation, clearly shows an imbalance of the trophic chain, towards the fermentative step. Thus, although the substrate removal remains more or less constant, this is reflected in a substantial increment of CO_2 in the biogas. To conclude this comparison, it seems reasonable to state that the temperature rise in the severe operative conditions analyzed leads to a situation of potential digester failure, in exchange for very limited advantages in terms of process performance.

Considering the comparison between periods 1 and 4, where the temperature difference is 6.5°C, a similar digester behaviour can be observed. In fact, in terms of process stability, an increase of VFA concentration was registered in going from period 4 to 1 (from 421 to 694 mg HAc/l). The other stability parameters remained approximately constant. However, both periods can be considered situated within a range of safe operating conditions, relatively away from those of digester failure. This is clearer comparing the yields of periods 1-4 with those of periods 2-3, and could be considered a consequence of the larger HRT=SRT used (8 days for periods 1-4 instead of 6 days for periods 2-3). In general, the conclusions that can be drawn in the match of periods 1 and 4 agree completely with those drawn in the previous comparison.

Finally, if f_B is considered the more representative yield (as it takes into account the methanization of the waste) it would appear that, within the critical range of conditions tested, the increase of temperature would act as a negative factor, in both couples of periods matched here.

Effect of OLR

Since in the semi-dry process the concentration of the feed sludge is maintained constant at about 20% TS, after temperature, the only other operative parameter able to represent the digester behaviour is the OLR.

Whereas the temperature, as stated above, reflects its influence mainly on the VFA concentration and in the percentage of CH_4 and, thus, in the f_B parameter, OLR shows a large influence on the biodegradation achieved. Within the range of operative conditions here considered, this relation turns out to be linear if OLR is plotted versus SGP. Taking into account data from Table 1, Figure 1 shows this plot. The correlation ($r^2 = 0.985$) is:

$$SGP = 0.498 - 0.0139\ OLR$$

Of course, the intercept,0.498 m^3 biogas/kg VS, has no meaning because when OLR approaches 0, SGP approaches G_0, according to a relation that cannot be linear throughout the whole range. A similar relation could be deduced in terms of the biodegradation achieved, that is between f_G and OLR, since $SGP/G_0 = f_G$.

According to the observations reported, on the one hand, VFA could be considered the parameter able to interpret the additional load produced by the temperature increment, which acts on the trophic chain balance and causes the change on the VFA yield; on the other hand, the OLR applied allows the choice of the operative conditions in terms of desired level of biodegradation to be achieved.

KINETICS

Two models have been selected to study the kinetics of the degradation: the first order and the step diffusional model (Mata-Alvarez and Cecchi, 1989). The first order model is well known and does not need further explanation. The step-diffusional model, much less known, is briefly described in the following paragraphs.

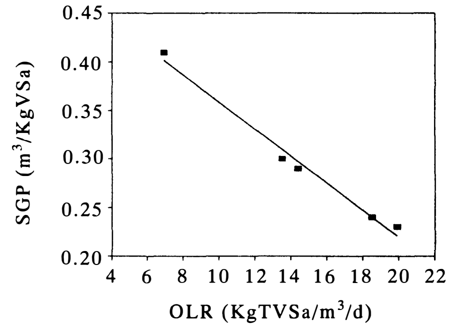

Fig 1. Linear reaction between the SGP and the OLR

Step-diffusional model

Anaerobic treatment of complex waste, such as the OFMSW, proceeds in accordance with several steps when a digester is fed on a semi-continuous basis (Cecchi et al., 1990b). These steps can be observed if, after feeding a digester, the biogas production rate is plotted vs time. Three different utilization rates can be identified, each one linked to the degradation of a specific group of compounds. Thus, during degradation of compounds which are directly used by methanogenic bacteria (group A), the kinetic equation is:

$$dS/dt = v_0 - k_0\, t/2 \qquad (1)$$

The slope of the straight line linked to the degradation of compounds of group A is k_0 and v_0 is the maximum degradation rate of these compounds. Similarly, during the degradation of monomeric compounds (groups B/C) and polymeric compounds (group D), the respective equations are:

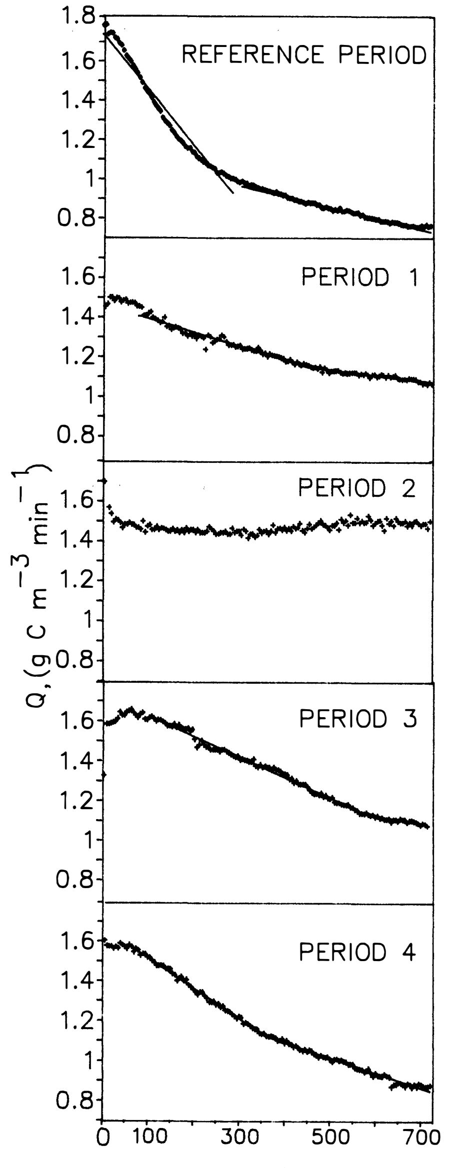

Fig. 2. Biogas production profiles in the periods considered

$$dS/dt = v_1 - k_1 (t - t_1)/2 \qquad (2)$$

and

$$dS/dt = v_2 - k_2 (t - t_2)/2 \qquad (3)$$

where t_1 represents the time needed to complete the first step (degradation of compounds of group A) and t_2 the time needed to complete the second step (degradation of compounds of groups B and C).

This model involves a number of constants, k_1, k_2 and k_3 on the one hand and v_0, v_1, and v_2, on the other. Further information related to this model can be found in Cecchi et al., 1990b where it has been proposed and its physical significance demonstrated.

These three steps are not always present in the biodegradation of a given waste: it depends on the characteristics of the substrate feed (groups of compounds present in it). For instance, when sewage sludge is used, only one step appears, as the substrate is mainly formed by compounds of group D (Cecchi et al., 1990c). When MS-OFMSW is fed at thermophilic conditions, two steps are present, which have been related to the degradation of compounds B/C and D (Mata-Alvarez et al., 1990).

Constant fitting

Figure 2 shows an average profile obtained operating the digester at the reference conditions shown in Table 1, which are far from the overloading observed in periods 1-4. Figure 2 (periods 1-4) shows the biogas production profiles obtained after feeding the digester in the four periods considered. These profiles can be used to fit the kinetic models selected. Concentration S has been estimated through the biogas production, passing it at g C/min. Table 2 shows the values of the constants fitted for both models. Looking at the slopes in the plots, two distinct types of fitting can be seen. The first corresponds to period of reference where two steps seem to control the biogas production rate (those corresponding to the degradation of compounds B/C and D). In the second type (periods 1-4) there is always present some kind of "plateau", occurring just after feeding the digester. The duration of this plateau is increasing in the following order of periods: 4, 1, 3 and 2. In the last, the plateau is complete, as it extends from one feeding to the following. Simultaneously to the formation of this plateau, the length of time of the second step (that corresponding to the degradation of compounds of group B/C) is observed. An explanation of this behaviour would be based on the increasingly shorter HRT's and larger OLR's used in periods 4, 1, 3 and 2. These factors could cause a decrease in microorganism/substrate ratio and a considerable increase in the soluble organic loading rate (the increase of temperature favours also the hydrolysis rate). As a consequence, a larger availability of soluble compounds per microorganism is produced and this substrate is no longer the limiting factor. Microorganism concentration now becomes the limiting factor in the biogas production rate and the reaction order approaches to zero. Therefore, once the digester is fed, biogas production tends to be constant. When a complete plateau is formed after the feeding operation, the reactor is operated near its limits.

TABLE 2 Fitted Kinetic Constants Corresponding To The Periods Studied

Period	**Ref.**	**1**	**2**	**3**	**4**
OPERATING CONDITIONS AND VFA					
T (ºC)	54.8	54.6	51.5	47.7	48.1
OLR (kg VS/m^3.d)	6.9	13.5	19.9	18.8	14.0
VFA (mg HAc/l)		525	694	2151	451421
FITTED CONSTANTS					
FIRST ORDER					
k (days^{-1})	1.61	0.71	-	0.96	1.34
STEP DIFFUSIONAL					
k_1 (gC/m^3.min^2)x10^3	3.6	0.9	-	1.0	1.5
k_2 (gC/m^3.min^2)x10^3	0.6	0.7	-	0.6	0.9
v_1 (gC/m^3.min)	1.79	1.47	1.51	1.73	1.67
v_2 (gC/m^3.min)	1.13	1.12	-	1.36	1.18

The analysis of the data shows the low influence of temperature on the constants fitted and confirms the low influence on the biogas yields. This can be explained because of the narrow range of temperature tested (6°C) which is not enough to reveal significant influences. In fact, taking into account the Arrhenius equation, this increase of temperature would increase the value of the first order constant by about 2%, which is within the range of the experimental error.

Analysis with the first order model

The first order kinetic constants fitted in the four periods studied here are all lower than that of the period of reference (1.61 day^{-1}). In fact, this constant could be considered as a measure of the stress of the conditions applied to the digester (in this case, coming either from the large OLR applied, or from the load introduced by the higher temperature). Looking at their values, it can be seen that in decreasing order, they are: 4, 3, 1 and 2 (the constant for this latter period can be considered practically zero). In fact, and as mentioned earlier, the true first order kinetic constant should be practically the same within this small range of temperatures tested. Thus, the approach of considering the profile of biogas production once fed the digester cannot be applied at overloading conditions. This approach can only be used if it is verified that the the digester has not been overloaded.

As mentioned earlier, the overload produced by the value of OLR or by the increase of temperature is reflected on the level of VFA. In fact, this is confirmed looking at the VFA concentration of these periods, which are reproduced in Table 2 to facilitate the comparison. The level of VFA is more responsible than the OLR considered alone. Thus, looking at the values of the constants of periods 1 and 3 (0.71 and 0.96, respectively), that of period 3 should be lower if the OLR were the factor affecting its value and this does not happen. On the contrary, VFA level shows a more homogeneous correlation, and seems to indicate that high levels of VFA inhibit the methanization. As mentioned before, this high level can come either from an increase of temperature of from the increase of OLR.

Analysis with the step diffusional model

Looking at the information which can be deduced applying the SD model (Table 2 and Figure 2), it can be seen that biogas production rate starting at the level of v_1 decreases accordingly with the slope measured by k_1. This slope is around three times lower in the periods considered in this study than in the reference period. The extreme is period 2, where no slope can be measured at all, due to the severe overload. However, in this case, it is possible to identify the v_1 constant, which is particularly assured the existence of the "plateau" in all the periods (Cecchi et al., 1990b). Its mean value, $v_1 = 1.59$, is quite comparable with that of the reference (1.79) or with the mean value obtained in thermophilic conditions in a previous study (1.65) (Cecchi et al., 1991). On the other hand, the values of v_2 are in agreement with that of the reference period, as are the slopes (k_2), once the "plateau" disappeared.

CONCLUSIONS

The severe conditions tested clearly demonstrate the feasibility of operating digesters at thermophilic conditions working at 6-8 days retention time and OLR around 20 kg TVS/m^3·d without stability problems. However, the biomethanization yields decrease as compared with periods without overloading.

The severe conditions are clearly reflected in the gas production curves which tend to be planar between one feed and the next. The existence of a "plateau" in the gas production rate curves leads to a decrease on the first order kinetic constants obtained. The limit can be represented by period 2, where the low HRT (6.1 days) and high OLR (19.9 kg TVS/m^3.d) used leads to a complete "plateau" in the gas production profile and, consequently, to a kinetic constant zero. The same decrease on the value of the kinetic constant k_1 is obtained when SD model is applied with the digester overloaded.

When the digester is operated at high stressing conditions, an increment of temperature produces an increment in VFA and, consequently, in the percentage of carbon dioxide in the biogas produced. The higher level of VFA also affects the value of the kinetics constants and the formation of the "plateau" mentioned above.

One methodological conclusion is that the use of the approach of plotting the biogas production rate after feeding is a useful tool in interpreting the performance of a digester.

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NOTATION

AD	anaerobic digestion
B_0	ultimate methane yield (m^3/kgTVS)
f_B	biodegradation with respect B_0, (%)
f_G	biodegradation with respect G_0, (%)
GPR	gas production rate (m^3/m^3.d)

G_0	ultimate biogas production (m^3/kg VS)
HRT	hydraulic retention time (days)
k	first order kinetic constant (day^{-1})
k_1	kinetic constant representing the proportionality constant between degradation rate and time for the acidogenic step (g C/m^3.min^2)
k_2	kinetic constant representing the proportionality constant between degradation rate and time for the hydrolytic step (g C/m^3.min^2)
MS-OFMSW	mechanically sorted organic fraction of municipal solid waste
OFMSW	organic fraction of municipal solid waste
OLR	organic loading rate (kg TVS/m^3.d) total phosphorus content (%TS)
Q	feed flow rate (m^3/d)
SCOD	soluble chemical oxygen demand (%TCOD)
SMP	specific methane production (m^3/kg TVSfed)
SGP	specific gas production (m^3/kg TVSfed)
SRT	solid retention time (days)
STS	soluble total solids (%TS)
SVS	soluble volatile solids (%TVS)
TA	total alkalinity (mg $CaCO_3$/l)
TA_4	total alkalinity measured at pH 3.8 (g $CaCO_3$/l)
TA_6	total alkalinity measured at pH 6.0 (g $CaCO_3$/l)
TC	total carbon (%TS)
TCOD	total chemical oxygen demand (%TS)
T	reactor temperature (°C)
TOC	total organic carbon (%TS)
TKN	total Kjeldahl nitrogen (%TS)
TS	total solids (g/kg)
TVS	total volatile solids (%TS)
VFA	volatile fatty acids (mg CH_3COOH/l)
v_1	maximum degradation rate for acidogenesis (g C/m^3.min)
v_2	maximum degradation rate for hydrolysis (g C/m^3.min)

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