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Bioenergy from waste activated sludge and market-waste: single and two phase thermophilic codigestion

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Results of 2 year pilot scale experiment are presented in this paper, considering different sets of operative condition using thermophilic range temperature in single and two phase process configuration. The research was carried out using a 200 l and 450 l working volume reactors, fed with activated sludge from a full scale biological nutrient removal (BNR) WWTP and market waste coming from separate collection. In the single phase test, after a start-up period feeding only waste activated sludge, the OLR applied was increased from 2 kgTVS/m^{3}d to 4 and 6 kgTVS/m^{3}d maintaining the amount of sludge and increasing the waste content. The SGP value during the start-up was 0,16 m^3/kgTVS, while in the next three period, with the addiction of organic fraction, the biogas production rate increase and the SGP value reach 0,51 m^3/kgTVS in the higher load period. In the two-phase run the OLR was increased gradually as in single–phase test. The first condition was studied at an OLR of about 1,5 kgTVS/m^{3}d in the second digester, feeding only waste activated sludge; in the successive step the digester was fed with 3,1, 7,2 kgTVS/m^{3}d and finally, considering the good process behaviour, the organic loading rate applied was increased to about 10,5 kgTVS/m^{3}d in order to stress the system. As supposed, the stability and biogas data confirm the better effectiveness of thermophilic range and two phase approach in high loaded processes, infact the SGP rose up from 0,10 (only sludge) to 0,43 m^3/kgTVS in the last period, while the gas production rate increase from 0,15 to 4,59 m^3/m^{3}d.

1. Introduction

The paper present the data coming from a EU research program (Cropgen), basically devoted to determine the benefits coming from co-digestion of agricultural and market wastes biomass and sewage sludge coming from wastewater treatment plant (WWTP). This mainly considering the possibility given by treat these substrates inside WWTP, reducing investment costs and treating liquid residues directly inside the plant. Moreover, in the next years, bioenergy will be one of the most important renewable energy source, like solar and wind power. The anaerobic co-digestion process could be the right solution for energy reclaim thanks to the great production of biogas and considering the availability of 36,000 digesters in EU that are in low loaded conditions.

2. Material and methods

The single phase test was studied in a 200 litres pilot scale plant in thermophilic conditions. The same reactor was used as first phase in two-phase investigations, followed by a 450 litres working volume digester. Both the reactors used were CSTR type, fed semi continuously once a day, maintained at 55 ± 1 °C using an external hot water recirculation. Biogas and temperature were monitored continuously, while other analytical parameters were determined following the Standard Methods procedures. Characteristics of the substrates are reported in table 1.

Table 1. Substrates characteristics

	Single phase				Two phase			
N° sample	**30**				**100**			
	Sludge							
	media	**min**	**max**	**s.d.**	**media**	**min**	**max**	**s.d.**
TKN (mgN/ gTS)	48.29	35.78	61.67	14.34	52.34	41.07	65.31	13.41
Ptot (mgP/gTS)	14.41	9.91	19.80	3.95	16.25	14.92	17.91	1.50
COD (mgCOD/ gTS)	697	427	960	193	940	298	1444	257
TS (g/kg)	29.9	22.5	38.4	5.1	25.2	21.6	32.2	3.5
TVS (g/kg)	18.70	14.36	24.46	3.86	15.62	26.18	19.69	1.57
%TVS	62.70	56.70	73.93	6.23	62.34	59.84	64.68	1.96
	Agro-wastes							
TKN (mgN/gTS)	29.3	17.1	36.8	7.0	29.8	25.7	33.5	4.9
Ptot (mgP/gTS)	5.42	3.10	7.96	2.62	3.40	3.15	3.61	0.32
COD(mgCOD/gTS)	891	783	981	85	865	721	1096	96
TS (g/kg)	253.2	189.3	310.7	42.9	261.7	222.5	296.1	13.2
TVS (g/kg)	202.80	155.73	42.56	29.23	222.92	190.65	248.19	19.94
%TVS	80.9	70.0	90.1	7.1	84.5	19.7	88.6	3.5

3. Results and discussion

3.1 Single phase test

The reactor was inoculated using mesophilic sludge coming from the full scale plant of Treviso and heated to thermophilic temperature in 48 hours. After a week, the process was started-up softly, feeding only waste activated sludge (OLR=0.7 kgTVS/m^{3}d). After the acclimation period, an increase of OLR was applied, increasing solid agro-wastes percentage in mixture, as shown in table 2. Treating only sludge, the low TVS removal is due to the poor biodegradability of the substrate, which are produced by a BNR plant working at an average SRT of 14-16 days. Considering the characteristics of this substrate (secondary sludge) it is possible to explain the low biogas production (GPR=0.12 m^3/m^{3}d, SGP=0.16 m^3/kgTVS, table 2). This situation is very common in recent WWTPs, where the lack of the primary clarifier, to maintain the whole COD for the biological denitrification step, shows how it is useful to integrate the organic load of the digester with high putrescible substrates. After the start up period, the organic waste was added to sludge in order to increase gradually the OLR from 2 up to 4 and 6 kg TVS/m^{3}d. However, considering the other typical stability parameters, such as alkalinity, ammonia and VFA content, no problem in process behaviour can be observed in all the periods. In fact, the progressive addition of waste during the test allowed an alkalinity improvement, as shown by the average data reported in table 2; concerning the ammonia content, it increase constantly , starting from 600 mgN/l and reach about 1500 mgN/l. This could be linked to the limit of the process, even if the specific toxic limit for ammonia content for waste treatment is much higher (4 gN/L) (Angelidaki & Ahring, 2003).

Table 2. Average values obtained in single and two-phase experiments.

	single-phase				two-phases			
	Start-up	**I**	**II**	**III**	***Start-up***	**I**	**II**	**III**
Fed parameters: Sludge								
pH	7,04	7,27	7,00	7,06	6,81	7,21	7,26	7,09
TS, %	2,17	2,48	3,04	3,46	2,19	1,69	3,67	3,95
TVS, %TS	62,0	60,3	67,0	60,8	62,7	64,3	60,6	60,9
Fed parameters: agrowaste								
TS, %		24,20	24,16	27,60		25,67	26,67	26,73
TVS,%TS		79,9	83,3	79,9		84,1	86,5	84,7
***Operational condition:* I° phase**								
OLR, $kgTVS/m^3_{reactor}d$					13,71	26,05	52,74	77,52
Temperature, °C					56±1	55±1	55±1	55±1
HRT, d					1	1	1	1
***Operational condition:* II° phase**								
OLR, $kgTVS/m^3_{reactor}d$	0,71	2,19	3,97	6,18	1,52	3,13	7,18	10,56
Temperature, °C	55±1	54±1	55±1	55±1	55±1	55±1	54±1	55±1
HRT, d	20,0	18,0	16,0	14,0	9,0	8,3	7,6	6,9
Digester parameters (*)								
pH	7,83	7,90	7,89	7,59	7,59	7,67	8,05	8,04
Alkalinity (@ pH 6), $gCaCO_3/l$	2049	1952	2345	2946	833	1808	3191	3788
Alkalinity (@ pH 4), $gCaCO_3/l$	2724	2767	3505	7000	2530	2921	5163	6241
Volatile fatty acids, mgCOD/l	156	70	200	321	124	87	151	399
Ammonia, mgN/l	598	687	1265	1473	416	640	1230	1334
TS reactor, %	2,15	2,70	4,20	6,21	2,13	2,15	4,37	4,04
TVS reactor, %TS	56,2	65,0	69,1	66,0	58,7	60,4	59,5	58,9
Yields								
GPR, $m^3_{biogas}/m^3_{reactor}d$	0,12	0,85	1,65	3,12	0,15	1,27	3,03	4,59
SGP, $m^3CH_4/kgTVS_{feed}$	0,16	0,41	0,42	0,51	0,10	0,41	0,42	0,43
CH_4, %				67		73	72	70

Figures 1-2 shows, as an example, the patterns of GPR and VFA during the whole experiments.

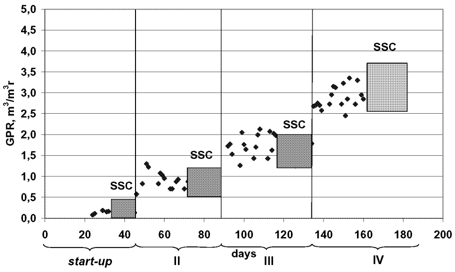

Figure 1. GPR trend during the experiments.

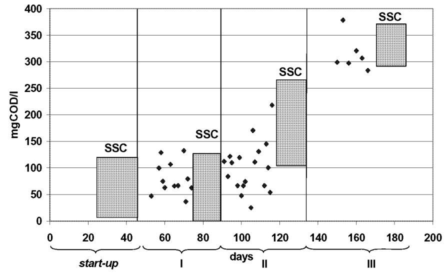

Figure 2. VFA trend during the experiments.

With particular reference to the process yields, figure 3 shows the influence of the increased load due to the addition of the agro-waste: the GPR increases linearly with the OLR in all the periods studied, from 0.1 m^3/m^3 per day, when only sludge was fed, to 3.12 m^3/m^3 per day with the higher OLR. In fact, figure 3 shows the linear relation between the two parameters: the correlation coefficient (R^2) is quite high (0.9903). Figure 4 shows the relation between OLR and SGP in the range studied. As can be seen, the relation is not linear, and the reaching of a plateau can be observed when OLR approaches to 6 kgTVS/m^3d.

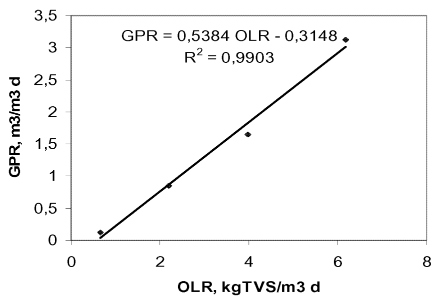

Figure 3. GPR vs. OLR in the experiments.

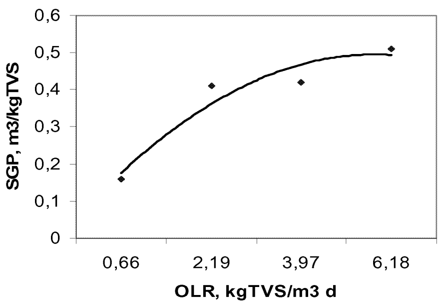

Figure 4. SGP vs. OLR in the experiments.

This value can be considered the limit for the process. These results are in good agreement with literature data (Bouallagui et al., 2005), which report typical biogas specific yields in the range 0.35 – 0.47 $m^3/kgTVS_{feed}$ when operating in thermophilic conditions with mixture of OFMSW and sewage sludge, but especially with the research carried out by Pavan et al., (2000), in which the same load is defined as the limit for the single phase thermophilic anaerobic digestion of SS-OFMSW alone.

3.2 Two Phase test

Also in two-phase configuration the amount of solid waste feed was increased trough three steps as in the single-phase test. The start-up of reactor was carried out using the sludge from previous single phase test for about half of the total volume (about 200 litres), and the rest using digested sludge from the full-scale plant of Treviso. The digester was maintained at 55 °C for 10 days without feeding, then the system was fed using sewage sludge alone for about three weeks. Then, an OLR of 3.13 kgTVS/m^3d was applied to the second phase. After the reaching of the SSC, the OLR was increased again to 7.18 kgTVS/m^{3}d; these conditions were maintained for a long time (150 days), due to a lot of problem in the market waste acquisition, reactor maintenance, on-line probes malfunction etc. The last operative condition applied was made in order to stress the system, feeding 10,56 kgTVS/m^{3}d. In figure 5 the pattern of the organic loadings applied to both reactors, is shown. In all three conditions, no evidence of system imbalance was found in the process.

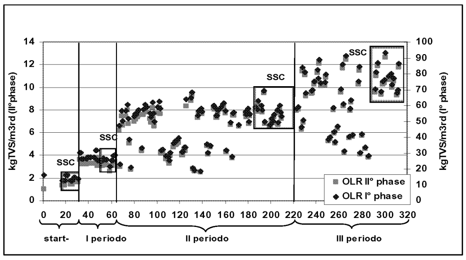

Figure 5. OLR trend during the experiments.

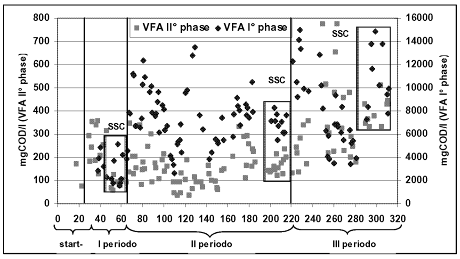

Figure 6. VFA trend during the experiments.

Observing the data obtained, the first phase can be seen as a pre-treatment of the mixture before the feeding of the second phase, obtaining a significative increase of VFA concentration and improvement of hydrolysis grade of the substrates (see fig. 6): the mixture reached values of about 6200 mgCOD l^{-1} after the first phase during the second period, while during the higher loading the VFA production in the first phase was 11200 mgCOD l^{-1}. This high load was treated without particular problems in the second phase, as can be seen from the pattern of VFA represented in fig. 6, where the VFA amount was about 400 mgCOD l^{-1}.

Considering the yields, a GPR value of 1.27 m^3/m^3 d was reached after only 7-10 days in period 1, even if a complete stable situation is obtained after 15 days, according to the stability parameters patterns. The SGP showed the same trend. The situation in period 2 is more complex, mainly due to the inconstant conditions of feeding during the first part of the period. The real stable condition can be considered after day 200, in which GPR reach and maintain a value of 3.03 m^3/m^3 d. The process behaviour give us the opportunity to increase again the organic load to 10,56 kgTVS/m^3; the GPR reach the 4,59 m^3/m^3 d, that is an important results in economic balance. Infact these results open feasible ways to enhance the economical balance of WWTP: in other words, it represent the possibility to increase of at least one order of magnitude the biogas production in the plant, completely changing the economical balance of the plant.

About SGP value evolution, all the three period show similar average value (0.41, 0.42, 0.43 m^3/kgTVS respectively), thus this value could be the 'plateau' level for the two phase experiment. The comparison between these data and the other obtained in single phase experiment (table 2).give very important information about the best approach to be followed

As can be seen, the two phase approach confirm the possibility to use high load condition without particular problem for stability parameters, with an interesting biogas production. This could means that this loading range (up to 4 kgTVS/m^{3}d) can be considered as a 'low' loading conditions, in which the single phase process can be applied without any problem. This observation is very important, because this means, for example, that the existing digesters treating sewage sludge in WWTP can be overloaded 'as it is' up to 4 kgTVS/m^{3}d using agrowastes or similar substrates

4. Conclusions

The work done has demonstrated as it is possible to implement the thermophilic codigestion process to treat activated sludge and agro wastes coming from markets. In particular:

- OLR ranging from 2 to 6 kgTVS/m^3d was investigated for the single phase, observing a completely stable situation in all the conditions studied. pH and alkalinity values were always in typical ranges. The addition of increasing amount of waste in the feed lead to an improvement in buffer capacity of the digester (from 2700 to 7000 mg $CaCO_3$/l);
- Biogas production (GPR) increase linearly with OLR, while the specific production reached a plateau when OLR approached to 6 kgTVS/m^3 d. This could be the process limit for these conditions;
- The comparison between single and two-phases process shows that at similar load condition there aren't significant differences, instead at high organic loading rate the hydrolysis reactor probably enable a better contact of substrate and biomass during the successive step, with a great biogas production.
- If it will be possible to apply on full-scale the operative condition studied in the last period of two-phases test, (i.e. 2000 m^3 of digester volume), the amount of biogas produced could be 9000 m^3/d instead 400-500 m^3/d obtained only with sewage sludge. This means an electric energy production of about 20,5 MWh/d plus thermal recovery.

5. References

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