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Mesophilic, Thermophilic And Temperature Phased Anaerobic Digestion Of Waste Activated Sludge

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This paper deals with a two-year pilot scale experimental trial for the mesophilic (35°C), thermophilic (55°C) and temperature phased (70°C+55°C) anaerobic digestion of waste activated sludge at high rate (total solids 6% in the feed). The reactor operated at an organic loading rate of some 2,2 kgVS/m^{3}d and a hydraulic retention time of 20 days in the three different temperatures tested. The general conclusion of this study is that a two phase processes with a first hydrolytic phase at 70°C can be a convenient solution to improve the stabilisation capability of anaerobic digestion of waste activated sludge and can be easily implemented for the upgrade of full scale wastewater treatment plants.

1. Introduction

Sludge treatment and disposal has been receiving increasing attention from environmental agencies and decision makers as sludge volumes are becoming higher and higher as a consequence of more stringent criteria for wastewater treatment plants (WWTPs) effluents. The disposal of biosolids, together with energy consumption for pumping and aeration and personnel, is the main cost in wastewater treatment works and may account for up to 50% of operating costs of a WWTP. According to this situation the performances of the sludge treatment processes need to be improved. Anaerobic digestion can play a key role in the reduction of excess sludge.
This paper reports the main findings from a three-year pilot scale experimentation on the mesophilic, thermophilic and temperature phased anaerobic digestion of waste activated sludge at high solids concentration (average 6% dry matter in the feed).

2. Materials and Methods

The experimental architecture of the study considered a first phase in mesophilic conditions (37°C), then the temperature was changed to the thermophilic environment (55°C) and after a transient period a new steady state condition in thermophilic conditions was reached while in the last part of the experimentation also a hydrolytic reactor working at 70°C was added for the pre-treatment of sludge before thermophilic anaerobic digestion. The waste activated sludge used in the tests showed the average

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characteristics of sludge after centrifuge thickening collected in two years of experimentation were those shown in table 1. The pilot scale anaerobic digester used as mesophilic reactor in phase 1 and thermophilic reactor in phase 2 and 3, was a 1,3 m^3 stirred reactor initially inoculated with sludge from a mesophilic reactor treating biological sludge. During phase 3 it was connected to an extreme thermophilic (70°C) anaerobic reactor for sludge pre-hydrolysis with a total volume of 0,2 m^3. All the analysis were carried out according to the *Standard Methods* while VFA were carried out by gas-chromatograph. In order to verify the tendency of sludge to undergo to dewatering filtration tests for the determination of the sludge resistance to filtration (SRF, m/kg) were carried out according to Sorensen and Wakeman (1996). Tests were carried out at a standard pressure of 49 kN/m^2 using Whatman 41 filters and volumes of 100 ml of sludge. The presence of *Salmonella* and *Escherichia coli* in digested sludge was also determined.

Table 1 – Characteristics of the thickened waste activated sludge (average on 617 samples)

		Avg	Std Dev	Min	Max
pH	(-)	6,4	0,1	6,3	6,7
TS	g/l	57,0	7,3	19,3	72,9
TVS	g/l	45,1	6,1	15,3	60,5
TVS	%	80	2	74	83
COD/TVS	(-)	1,6	0,48	0,69	3,26
TKN	%	7,5	1,20	4,7	9,8
TP	%	1,9	0,5	0,2	3,1

3. Results and Discussion

The experimentation considered a first period in which the 1,3 m^3 volume anaerobic digester operated in mesophilic conditions, a second period in thermophilic conditions and a third condition with a dual phase process as described in the experimental section. In the three experimental runs the total solids concentration in the feed was some 6%, the HRT 20 days and the corresponding OLR some 2,2 $kgVS/m^3d$. Table 2 summarises the operational conditions applied o the reactors during the experimentation: it was observed an increasing average biogas production which passed from 0,88 m^3/d in mesophilic conditions to 1,23 m^3/d in thermophilic conditions and up to 1,33 m^3/d in the two phase temperature phased system. Table 3 shows the typical yields and characteristics of the reactor effluent along the experimentation.

What turned out evident from the data reported in Table 3, was a clear increase in terms of volatile solids and COD removal when increasing the reactor temperature and passing from one to two phases processes: this resulted then in an increase in biogas production. With specific reference to the results of the one-stage runs, phase 1, when the reactor operated in mesophilic conditions, showed results slightly higher than those expected for this process (Bolzonella et al, 2005): SGP was some 0,33 $m^3/kgVS_{fed}$ and

VS and COD removal 36% and 35% respectively. As for the stability parameters, pH was 7,8, total alkalinity 8.400 mg$CaCO_3$/l, values higher than those typically found in digesters treating only WAS (Bolzonella et al., 2005), while volatile fatty acids were just 570 mg/l.

Table 2 – Operational conditions

Run		Temperature, °C	Sludge, %TS	HRT, d	OLR kgVS_{fed}/ m^3d
1	Meso	37	6	20	2,1
2	Thermo	55	6	20	2,3
3	2 phase – reactor 1	70	6	2	15,0
	2 phase – reactor 2	55	5	18	2,3

After the study of the process in mesophilic conditions, it was decided to increase the reactor temperature from 37°C to 55°C (thermophilic). After a first period of failure, the system recovered and a steady state condition at 55°C was maintained for some 4-5 HRTs. In these conditions the gas production passed from 0,88 to 1,23 m^3/d (39% increase): this result is in full agreement with previous findings of the authors and those reported in literature. Bioags productivity on VS fed and VS removed increased passing from 0,33 to 0,45 m^3/kgVS_{fed} and from 0,8 to 0,9 m^3/kg$VS_{removed}$, respectively. This increase in biogas production was the result of increased VS and COD removal.
Also in this case the process was very stable (see pH, alkalinity and Volatile fatty acids). All these data confirmed the feasibility of increasing from mesophilic to thermophilic conditions the anaerobic reactors treating sludge with a considerable increase in biogas production (some 30%) and no consequences for the process stability.
In the last part of the experimentation, sludge was firstly fed to a 200 litres stirred reactor working at 70 °C (Bolzonella et al., 2007). This operated an accelerated hydrolysis of the sludge which was then fed to the methanogenic step, working at 55°C. The operational conditions for this second reactor were the same of previous experimental phases: 20 days of HRT and an OLR of some 2,2 kgVS/m^3d.
As for the first reactor this operated with a hydraulic retention time of 1 day and an OLR of 15 kgVS/m^3d: the characteristics of the sludge effluent are those shown in table 4. The most interesting data are those related to the concentration of soluble COD, some 19,6 g/l, and to VFA, whose average concentration was some 7,9 g/l. Acetic acid, propionic, butyrric and and valeric acid were the main compounds found in the acid mixture, with average concentrations of some 3, 2 and 1,5 g/l (both butirric and valeric), respectively. The specific VFA production was some 0,33 gCOD/gVS_{fed}. These results are in good agreement with those found at lab scale from the authors (Bolzonella et al., 2007). Because of the hydrolytic pre-treatment the second phase (methanogenic) showed a further increase in yields compared to the single-stage mesophilic and thermophilic trials. In fact, VS and COD removal were 55% (both), compared to 48% and 45% and 36% and 35% in thermophilic and mesophilic conditions, respectively, thus biogas production increased up to 1,33 m^3/d with a 48% increase compared to the mesophilic condition and a 12% compared to the thermophilic one.

Table 3 - Yields and stability parameters for the experimental runs

Average values		Phase 1 Mesophilic	Phase 2 Thermophilic	Phase 3 2 phase
	Stability parameters			
Total solids	%	4	3,5	3,1
Total volatile solids	%TS	73	70	70
pH	(-)	7,8	7,8	7,9
Total Alkalinity (pH 4,3)	$mgCaCO_3/l$	8.400	7.970	8.920
Partial Alkalinity (pH 5,7)	$mgCaCO_3/l$	6.500	5.980	6.660
VFA	mg/l	570	710	830
Ammonia	mg/l	2.380	3.130	3.440
	Yields			
VS removal	%	36	48	55
COD removal	%	35	45	55
Biogas production	m^3/d	0,88	1,23	1,33
Biogas production rate	m^3/m^3d	0,7	1,0	1,1
Biogas productivity	$m^3/kgVS_{fed}$	0,33	0,45	0,49
Biogas productivity	$m^3/kgVS_{rem}$	0,8	0,9	1,0

As a consequence, all the specific parameters showed higher values compared to the results of phase 1 and 2: SGP was 0,49 $m^3/kgVS_{fed}$ and SGP on destroyed VS reached 1,0 $m^3/kgVS_{rem}$ a value generally found in anaerobic digestion processes treating primary and mixed sludge.

3.1 Related aspects: nutrients, sludge dewatering, pathogens

The increased hydrolysis capability determined on one hand the increased biogas production and reduction of the sludge volume but also the increased presence of ammonia in the anaerobic supernatant, which passed form some 2 to some 3 gN per litre with a 33% increase. This aspect should be considered when performing the economic consideration for the process implementation at full scale. Phosphorous, on the contrary, did not show variations of the concentration in the soluble phase, probable because of its precipitation. Another important aspect to be considered in these kind of studies is related to the dewaterability of digested sludge; in fact, anaerobic digestion processes are known to affect various sludge properties including particle size distribution, extracellular polymeric substances concentration and composition, bound water content, and consequently the dewatering characteristics of sludge, therefore improved or decreased separation efficiency are often reported in literature (Subramanian et al., 2007). In this study the filtration resistance tests showed that mesophilic sludge

presented the worst results in terms of resistance with SRF values of some $1,8x10^{15}$ m/kg for raw sludge.
Also in this case the process was very stable: it reached immediately a steady state condition after the hydrolytic step was implemented and all the stability parameters were equivalent to those observed in thermophilic conditions.
These improved for flocculant dosage of 3 and 6 g/kg, reaching a final value of $8,0x10^{14}$ m/kg. On the other hand, thermophilic sludge showed better results for raw sludge (SRF of 1,1 $x10^{15}$) but only partially improving for increased polymer dosing: also in this case the final SRF value was $7,9x10^{14}$ m/kg at a dosage of 6 g/kg comparable to the result obtained for the mesophilic sludge. The sludge from the temperature phased system showed the better results with a SRF value of $8,0x10^{14}$ m/kg without polymer dosing, which improved linearly for dosage of 3 and 6 g/kg, with a final value of $1,6x10^{14}$ m/kg. As for the presence of pathogens, it was clear that the increased temperature determined a strong improvement in sludge quality: *Salmonella* was always absent in all tested samples, while with reference to *Escherichia coli* this was present at levels of some $1x10^{7}$ CFU both in mesophilic and thermophilic conditions while it was absent in the two phase systems because of the pasteurisation effect of the 70°C first phase.

Table 4 – Sludge characteristics of the 70°C reactor

Parameter		Average value	Bolzonella et al., 2007 (HRT 1 d)
pH		6,3	6,7
TS	g/l	56	30
TVS	g/l	45	22
TVS	%TS	79	74
SCOD	g/l	19,6	9,0
SC-VFA	g/l	7,9	7,0
Acetic	%	35	38
Propionic	%	25	21
iso- + n-Butirate	%	25	17
iso-Valerate	%	18	18
Alkaliny @ pH 4,29	$gCaCO_3/l$	6,5	3,6
Alkaliny @ pH 5,75	$gCaCO_3/l$	1,5	1,2
$SCOD/VS_{fed}$		0,33	0,30

3.2 Economics

According to the results found in this experimentation, the temperature phased process can be an interesting option for the up-grade of anaerobic reactors treating waste activated sludge especially when the treatment of high organic loading is requested (over-loaded systems). Economic evaluations performed for a 100.000 pe WWTP showed that the application of a two-stage process is a feasible alternative for sludge treatment: the introduction of a 70°C reactor can be pay back in some 2-6 years, depending on the way and costs of disposal of sludge (Bolzonella et al., 2007). .

4. Conclusions

The main findings of the study can be summarised as follows:

- the thermophilic and two phase temperature phased processes showed clear increases in terms of organic matter removal and biogas production compared to the mesophilic process; in particular the volatile solids removal passed from 36% in mesophilic conditions to 48% in thermophilic conditions to 55% in the temperature phased system. As a consequence the specific biogas production was 0,33 m^3/kgVS, 0,45 m^3/kgVS and 0,49 m^3/kgVS, respectively;
- the increased hydrolysis of the organic matter in thermophilic conditions determined an improved concentration of ammonia nitrogen and soluble COD in the anaerobic supernatant (+33% and +100%, respectively). This extra-load needs to be treated in the wastewater treatment line;
- the SRF for the raw effluent sludge was $8{,}0 \times 10^{14}$ m/kg without polymer dosing, which improved linearly for dosage of 3 and 6 g/kg, with a final value of $1{,}6 \times 10^{14}$ m/kg;
- the temperature phase systems allowed for the sanitation of treated sludge: *Salmonella* and *Escherichia coli* were absent in the two phases effluent;
- the temperature phased process with a first step at 70°C can be an interesting option to upgrade the process for over-loaded anaerobic reactors easily implemented in existing wastewater treatment plants with relatively short (< 6 years) pay-back time.

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