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Two-Phase Anaerobic Digestion of Waste Activated Sludge: Effect of an Extreme Thermophilic Prefermentation

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This paper deals with the application of a two-phase anaerobic digestion process where the first phase operates at extreme thermophilic conditions (70 °C). The first reactor was fed with waste activated sludge and operated continuously at a hydraulic retention time of 1, 2, 3, and 5 days. Pretreated sludge was characterized by high concentrations of soluble COD (30−40% of the influent particulate COD) and VFA contents. Acetate, propionate, and isovalerate were the main compounds detected. The kinetic constant for the hydrolysis process was determined in 0.17 day^{-1}. Batch tests for the following anaerobic digestion and biogas production showed how the pretreated sludge determined better performances in terms of biogas production. The gas production showed increases in the range 30−50% for pretreatments of 2−3 days compared to the mesophilic and thermophilic single-stage tests. A calculation for a 100 000 people equivalent wastewater treatment plant showed that the increased biogas production allowed maintenance of the thermophilic conditions in both the first and second stages of a two-phase process and recovery of the investment costs in some 3−4 years.

1. Introduction

Sludge treatment and disposal is receiving increasing attention as sludge volumes are becoming higher and higher as a consequence of more stringent criteria for wastewater treatment plant (WWTP) effluent and due to the building of new treatment facilities.

A report from the European Commission[1] stated that in 2002 sludge production in Europe was some 12 million tons (dry matter): 80% of sludge was produced in western countries. Because of the different levels of services, specific sludge production was some 80−100 and 40−50 g of dry matter per person equivalent per day in western and eastern countries, respectively. Biosolids (sludge after treatment) are now disposed of in several ways, as shown in Table 1, with different final costs:[1,2] sludge disposal still represents up to 50% of the managing costs in a WWTP.[3] Some countries have established routes to beneficial recycling (land and forestry application, nutrients reclamation, etc.), even though this can create problems with micropollutants spreading, while other countries prefer incineration (e.g., Japan or Switzerland) and losing valuable matter; in any case it is clear that the production of excess sludge should be reduced.[4] However, because of new legislation, the disposal of biosolids is difficult since land application and landfilling are becoming almost forbidden,[5] so the enhancement of mineralization and reduction of sludge volume is a must in the field of environmental engineering. Reduction of sludge can be obtained by either manipulating the activated sludge process or improving the sludge treatment section.

When considering sludge treatment, in order to improve the stabilization rate and energy reclamation, waste activated sludge can be conveniently pretreated prior to being stabilized through an anaerobic digestion process; pretreatment techniques proposed in recent years are based on chemical, physical, and biological processes or combinations of those.[5,6] Recently, biological pretreatments have received particular attention for industrial applications because of their efficiency and relatively low investment. A particular kind of biological pretreatment is the application of a hydrolysis step before methanization, realizing a two-step anaerobic digestion process where the two stages generally operate at different temperatures. These processes are called two-phase or temperature phased processes.[11,14] Ahring and co-workers,[10,13] in particular, have proposed a first stage in extreme thermophilic conditions.

Table 1. Costs for Sludge Disposal[1,2]

sludge disposal	percentage of disposal, %	disposal costs, euros/ton
agriculture	46	100−270
landfilling	27	150−400
incineration	20	300−600
composting	7	150−400

Table 2 reports a summary of the main findings reported in recent literature with particular attention to two-step anaerobic digestion of waste activated sludge. In the table, process performances are compared in terms of yields as TVS reduction, organic matter solubilization, VFA production, and SGP at different conditions.

Data reported in Table 2 show how the highest increase in TVS removal and VFA concentration is obtained for temperatures over 60 °C and hydraulic retention times as short as 2−3 days: in that situation the dissolved COD represents up to 30% of the total COD while VFA concentrations are in the range 0.3−7.9 g/L depending on the total solids concentration in the reactor.

Another important point concerning the treatment of excess sludge is that the increased request of nutrients removal during wastewater treatment determined the revamping and upgrading of a number of WWTPs. Generally, the elimination of primary settlers is a usual practice for improving the performances for

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Table 2. Experimental Results from Previous Studies on Two-Phase Anaerobic Digestion of Sludge

pretreatment step temp, °C	pretreatment step HRT, day	dissolved COD, %	VFA concn, mg/L	total removed TVS, %	SGP increase, %	ref
35	2	4.8	5333	42.7		7
47	2	22.4	1466	25.9	69	3
54	2	25.3	2025	26.3	81	3
55	0.2		408	45	29.5	8
55	21			58	3.5	9
55	3.5	11.8	1565			10
60	5.5			60	16.6	11
60	0.2		291	56	−19.3	8
60	2	38.9	3068	34.5	98	3
60	3.5	15.2	2191			10
62	1			61	26.9	12
65	3.5	17.3	3913			10
70	4				144.6	13
70	3.5	27.8	7981			10
75	3.5	29.5	7512			10
80	3.5	30.5	7043			10

nutrients removal in the activated sludge process. As a consequence, only waste activated sludge is produced in these plants. Unfortunately, biological sludge shows a low tendency to biodegradation and thus low biogas yields,[15,16] especially if long retention times are applied in the activated sludge process.

On the basis of these considerations and findings from previous studies, this paper deals with the application of an extreme thermophilic (70 °C) fermentation process of waste activated sludge, in order to enhance sludge solubilization for maximization of biogas production in the following anaerobic digestion process. In particular, the aim of the work was to investigate the kinetics of hydrolysis and VFA formation and specific composition in the prefermentation step. Therefore, different operational conditions, in terms of hydraulic retention time, HRT, and organic loading rate, OLR, were applied to the hydrolyzing reactor. These allowed the determination of the kinetic constant for the hydrolytic process at 70 °C. Results from laboratory-scale tests allowed the calculation of energy balances and performances for a possible full-scale application of the two-phase process in a 100 000 PE WWTP.

2. Materials and Methods

The experimental work was divided into two main activities: the study of the prefermentation process of waste activated sludge at 70 °C in a continuous stirred tank reactor (CSTR) and the batch tests for AD of prefermented sludge. These were compared with results from mesophilic (37 °C) and thermophilic (55 °C) single-phase tests used as reference.

2.1. Prefermentation Tests at 70 °C in Stirred Reactors. Prefermentation tests were carried out in a stirred reactor, a flanged glass vessel with a 10-L working volume maintained at 70 °C. Feed addition and digestate removal were via stopper ports. Biogas was collected by a tube at the headspace top, and its production was measured by a Milligascounter MGC-1 (Ritter Gaszähler, Bochum, Germany). The reactor was inoculated with sludge taken from the anaerobic digester of Verona WWTP[16] and maintained at 70 °C for some 6 months to obtain an extreme thermophilic biomass before starting the feeding. During the experimentation the reactor was fed with waste activated sludge with the characteristics shown in Table 3.

The operational conditions applied to the extreme thermophilic continuous reactor during the experimentation are reported in Table 4. Any single condition was maintained for at least 5 HRTs to obtain steady-state conditions.

Table 3. Characteristics of the Sludge Used for the Reactor Feeding

parameter	mean	minimum	maximum	no. of samples
TS, g/L	37.3	33.0	42.0	48
TVS, g/L	29.7	21.0	37.0	48
TVS/TS, %	79.2	59.2	82.4	33
COD, g/L	32.6	28.3	42.0	22
COD/TVS	1.2	1.0	1.4	22
dissolved COD, g/L	2.0	0.4	5.0	36
pH	6.4	6.2	6.8	45
alkalinity at pH 5.7, g of $CaCO_3$/L	0.6	0.4	0.7	12
alkalinity at pH 4.3, g of $CaCO_3$/L	1.2	1.0	1.3	12
TKN, % (on dry matter)	4.7	3.3	5.1	12
NH_3-N, g/L	0.3	0.02	3.1	12
total P, % (on dry matter)	1.0	0.6	1.6	14
PO_4-P, g/L	0.1	0.02	0.31	14

Table 4. Operational Conditions Adopted during the Study for the First Reactor

operational conditions	run 1	run 2	run 3	run 4
temperature (°C)	70	70	70	70
HRT (days)	5	3	2	1
OLR (g of TVS/(L day))	6.5	10.1	14.8	28.9

2.2. Analytical Methods. The reactor was monitored by analyzing daily grab samples of the influent and effluent streams. Main parameters were determined in order to study the process stability and yields as well as the mass balances. The parameters COD, TS, TVS, TKN, and total phosphorus were determined according to *Standard Methods for Water and Wastewater Analysis* (1998). Alkalinity was measured by pH titration using 0.1 M HCl to endpoints of 5.75 and 4.3, and the results were expressed as partial alkalinity (PA) and total alkalinity (TA), respectively. The TVFA concentration and quality was quantified by gas chromatography using a Carlo Erba GC equipped with a flame ionization detector and a Nukol silica capillary column by Sigma Aldrich-Supelco.

2.3. Batch Biomethanization Potential Assays. The methane production potential of waste activated sludge, with or without pretreatment, was determined by means of batch tests at 37 and 55 °C. For these tests glass flasks were used, each with a working volume of 1 L, closed with butyl caps and aluminum crimps; the flasks were flushed with nitrogen during feeding for anaerobic conditions. The initial substrate/inoculum ratio for each experiment was determined according to Angelidaki and Sanders.[17] This corresponded to a preferential value of 0.25/0.75 as substrate/inoculum ratio in terms of VS. No minerals and buffers were added. All the experiments were carried out in triplicate. These were compared with the results of blank tests, where only the biogas produced by the inoculum was measured, and reference tests, where cellulose was digested. Biogas was measured with a liquid displacement method (acidic water) while the methane content was then determined as the difference after adsorption of CO_2 in a caustic solution (NaOH, 40 g/L). Inoculum came from an active laboratory-scale anaerobic digester treating waste activated sludge in both mesophilic and thermophilic conditions and had a typical activity of some 0.1 g of COD-CH_4/g of VS per day.

3. Results and Discussion

3.1. Extreme Thermophilic (70 °C) Anaerobic Hydrolysis. The main aim of the extreme thermophilic treatment of waste activated sludge in anaerobic conditions was to intensify the solubilization of particulate COD to simple soluble COD and so to obtain readily biodegradable compounds and improve the

Table 5. Control Parameters and Yields of the Extreme Thermophilic Continuous Reactor

pretreated sludge	HRT = 5 days	HRT = 3 days	HRT = 2 days	HRT = 1 day
TS (g/L)	31.3	30.9	29.5	29.9
TVS (g/L)	22.8	23.1	22.2	22.3
TVS (%)	72.6	74.5	75.1	74.5
total COD (g/L)	27.9	30.2	32.4	30.4
soluble COD (g/L)	12.1	10.4	9	9
VFA (g of COD/L)	9.0	8.4	6.5	7.0
TKN (g of N/L)	2.2	1.8	1.8	2.1
NH_3 (g of N/L)	1	0.8	0.6	0.9
P_{tot} (g of P/L)	0.9	0.7	1.1	0.8
P-PO_4 (g of P/L)	0.01	0.03	0.06	0.1
pH	6.8	6.8	6.8	6.7
alkalinity at pH 5.75 (mg of $CaCO_3$/L)	1157	1244	1323	1198
alkalinity at pH 4.3 (mg of $CaCO_3$/L)	3639	3657	3659	3658
yields	**HRT = 5 days**	**HRT = 3 days**	**HRT = 2 days**	**HRT = 1 day**
GPR (L_{biogas}/($L_{reactor}$ day))	0.12	0.40	0.75	1.15
SGP (L_{biogas}/g of TVS_{fed})	0.04	0.04	0.05	0.04
CH_4 (%)	40	40	39	39
CO_2 (%)	58	58	61	61
H_2 (%)	2	2	0	0
H_2S (ppm)	156	168	172	153
SCOD/TVS (g of SCOD/g of TVS)	0.43	0.35	0.36	0.30
$SCOD_{out}/COD_{in}$ (%)	35.7	32.1	27.1	28.4
TVFA (% SCOD)	73.1	88.1	66	73.3
TVS removal (%)	16.5	23.8	25.3	22.8

performances of the following anaerobic digestion step. Four different experimental conditions were tested in the 70 °C CSTR: these are reported in Table 4.

The efficiency of the prefermentation processes and the yields were determined considering both the influent and effluent characteristics. Table 5 summarizes the average conditions observed during the experimentation. With specific reference to data reported in Table 5, the concentration of total solids in the effluent of the system remained constant during the experimentation at a concentration of some 30 g/L, disregarding the HRT and OLR applied to the reactor. This value was 20% less than the influent concentration (37 g/L, see Table 3). The same was observed for the volatile solids, whose concentration remained at 22−23 g/L in the four experimental runs compared to the 30 g/L of the influent sludge (some 30% removal). When the total COD was considered, the concentration of this parameter in the effluent of the CSTR ranged between 28 and 32 g/L in the four experimental runs, a value very similar to the influent COD (32 g/L). The difference among the four experimental periods became clear when considering the concentration and composition of the soluble fraction of the effluent COD: in fact, increasing the HRT from 1 to 5 days resulted in an increase of the soluble COD concentration from 9 to 12 g/L; that is, 30% of the total COD in the effluent was soluble. The same trend was observed also for the short-chain volatile fatty acids (SC-VFA, from C2 to C5): those showed an increase from 7 to 9 g/L (these data will be discussed below). As a matter of fact, the main effect of the extreme thermophilic pretreatment was the dissolution of the particulate organic matter with formation of soluble organic compounds mainly characterized by a low molecular weight. The evidence of a solubilization process is also supported by the increase of ammonia concentration: that passed from 0.1 g/L in the influent to some 1 g/L, as N, owing to the protein hydrolysis and release.

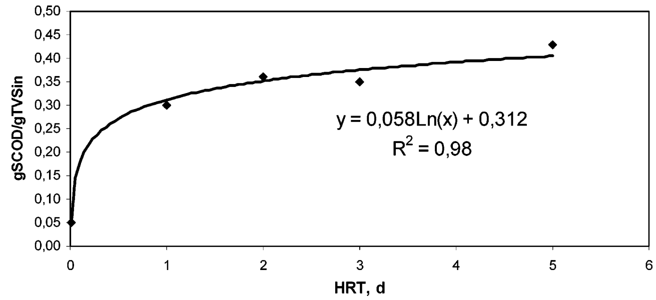


Figure 1. Yield of soluble COD per gram of volatile solids.

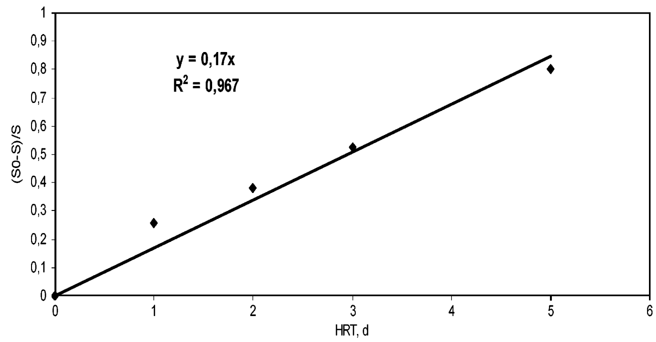


Figure 2. Determination of the hydrolysis constant for the extreme thermophilic reactor.

With specific reference to other parameters, pH remained constant at 6.8, while total and partial alkalinity were 3.6 and 1.2 g of $CaCO_3$/L, respectively, during all four periods.

As for the yield parameters, the biogas production increased according to the increasing OLR. The gas production rate increased from 0.12 to 1.15 L_{biogas}/($L_{reactor}$ day) passing from 6.5 to 30 g of TVS/(L day). The observed specific biogas production was 0.04 L per g of TVS fed to the reactor. Its composition was 60% carbon dioxide and 40% methane, while hydrogen was virtually absent, as expected under these conditions: previous studies showed that hydrogen is produced by anaerobic fermentation of sludge at pH values lower than 5.[18]

3.1.1. Soluble COD and VFA Production. The concentration of soluble COD in the reactor increased from 9 to 12 g/L with increasing retention time from 1 to 5 days. According to the results reported in Table 5, the yield of specific production for the soluble COD passed from 0.3 to 0.45 g of SCOD/g of TVS_{fed}. The yield followed a logarithmic behavior, where the formation of SCOD (as SCOD per gram of TVS) is a function of the applied HRT (see Figure 1).

Short-chain volatile fatty acids (SC-VFA) were determined as the sum of the acids from C2 (acetic) to C5 (valerate). Table 6 shows a summary of the experimental findings. The VFA concentrations in the fermented sludge passed from 7 to 9 g/L with increasing retention time of the reactor. As expected, acetic acid was always the main compound found in the effluent, its concentration being in the range 2.6−4.3 g/L; that is nearly half of the produced acids. Then, propionic and isovaleric acids were the most abundant compounds in the acid mixture with an average concentration of some 1.5 g/L each, except for *i*-C5 at HRT = 3 days, which reached a concentration of some 2.5 g/L. Butyric acid was present at a constant concentration of some 0.4−0.5 g/L, while *n*-valeric acid was nearly absent (generally <0.1 g/L). What is very important to focus on is the SC-VFA distribution with high and similar concentrations for acetic, propionic, and isovaleric acids. These results are in good agreement with previous findings of other researchers.[19,20] According to the results reported in Table 6, it is expected that

Table 6. TVFA (C2−C7) and SC-VFA (C2−C5) Concentrations

HRT, days	TVFA, g/L	C2, g/L	C3, g/L	*i*-C4, g/L	C4, g/L	*i*-C5, g/L	C5, g/L
5	9.0	4.3	1.5	0.5	0.5	1.4	0.1
3	8.4	3.3	1.5	0.5	0.5	2.5	0.1
2	6.6	2.6	1.4	0.7	0.5	1.3	0.05
1	7.0	2.7	1.6	0.7	0.5	1.3	0.01

Table 7. SGP (STP) for Waste Activated Sludge before and after Pretreatment in Mesophilic and Thermophilic Conditions

pretreatment HRT, days	incubation temp, °C	SGP, L/g of TVS
0	37	0.24 ± 0.02
0	55	0.43 ± 0.04
1	37	0.31 ± 0.03
1	55	0.54 ± 0.10
2	37	0.37 ± 0.02
2	55	0.59 ± 0.04
3	37	0.37 ± 0.04
3	55	0.65 ± 0.12
5	37	0.33 ± 0.03
5	55	0.63 ± 0.13

butyrate was easily degraded to acetic acid while *n*-valeric acid was transformed into acetic and propionic acids. On the other hand, isovaleric acid, a typical product of amino acid fermentation,[21,22] was hard to degrade and accumulated in the reactor at a level similar to those observed for acetic and propionic acids, probably because of a slow degradation rate or inhibition problems due to pH, ammonia, or VFA levels.[23] The fact that isovalerate accumulated in the prefermentation reactor can be probably ascribed to the hard degradation of branched forms. Some studies showed that iso forms of fatty acids are degraded slowly compared to the normal forms in anaerobic digesters.[19,20,22,24] It was suggested that isobutyrate and butyrate underwent β-oxidation and were easily transformed into acetate. Also the degradation of *n*-valerate followed β-oxidation with the production of propionate and acetate, while isovalerate isomerization was not observed. Batstone et al.[22] in a study dealing with the anaerobic oxidation of linear and branched chains of butyrate and valerate proposed that the stoichiometry of isovalerate degradation gives acetate and hydrogen as byproducts, according to the reaction $C_5H_{10}O_2 + CO_2 + 2H_2O = 3C_2H_4O_2 + H_2$, without any formation of propionate.

All these studies support the findings of this research: anaerobic fermentation of WAS at short HRT and high temperature produces acetate, proprionate, and isovalerate while butyrate and *n*-valerate are easily degraded to shorter forms.

3.1.2. Determination of the Hydrolysis Constant. To better describe the hydrolysis process, a first order kinetics model was applied to the continuous anaerobic reactor. The mass balance equation for substrate (the particulate COD) gives

$$QS_0 - QS - k_h VS = 0$$

where Q is the flow rate (L/day), S_0 is the influent substrate concentration (g/L), S is the effluent substrate concentration (g/L), k_h is the hydrolysis constant (day^{-1}), and V is the reactor volume (liters). Rearranging the variables, the following equation is obtained:

$$\frac{S_0 - S}{S} = k_h(\mathrm{HRT})$$

If we plot the term $(S_0 - S)/S$ versus HRT, we obtain the straight line of Figure 2, whose slope gives the hydrolysis constant, k_h (day^{-1}).

The regression curve was a straight line ($R^2 = 0.967$), and this fact confirms the applicability of a first order kinetics model. The slope of the straight line was the kinetic constant k_h, whose value was found to be 0.17 day^{-1}.

This value can be compared to those found in other works reported in the literature: it was found that the typical value of k_h for sewage sludge instead of waste activated sludge is in the range 0.25−0.40 moving from 35 to 55 °C.[23−26] However, a value of 0.15 at 55 °C was also observed.[27]

3.1.3. Mass Balance of the Stirred Reactor. According to data reported in Tables 3 and 5, the mass balances of the single species were calculated. Figure 3 shows the mass balances of the four experimental periods for the parameter total and volatile solids, COD, soluble COD, nitrogen, and phosphorus.

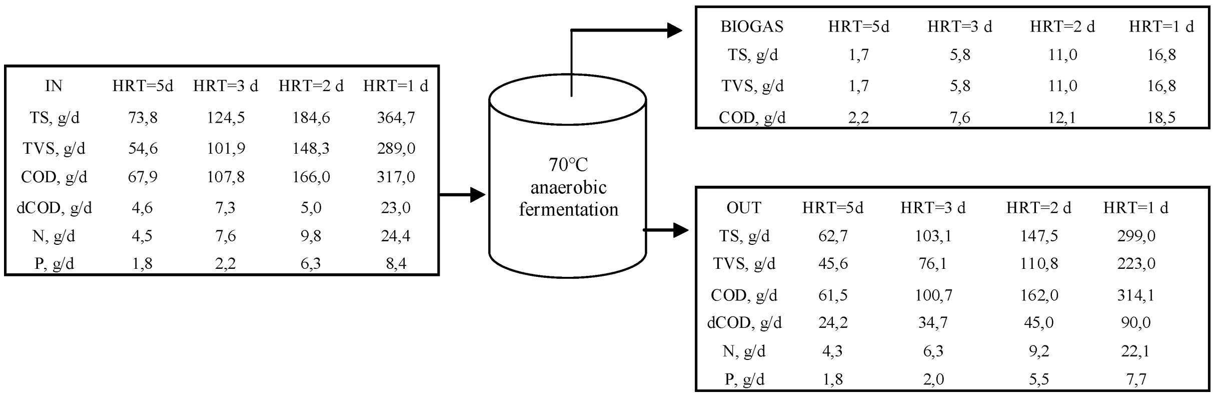
The mass balances for TS and TVS showed that these were only partially removed through biogas formation (only 20−30%) and were rather transformed into soluble organic compounds. This was shown also by COD data: only 5% (on average) of the COD was removed as CO_2 and CH_4 while the rest was solubilized, with VFA being the main product of fermentation. As for nutrients, nitrogen and phosphorus, these were just hydrolyzed. In fact, influent nitrogen was present as proteins, while half of the effluent nitrogen was ammonia. All the mass balances closed with an error <10%.

3.2. Tests for Anaerobic Digestion of Normal and Pretreated Waste Activated Sludge. The sludge treated in the anaerobic extreme thermophilic continuous reactor was used to perform batch experiments for the determination of the biomethane potential of sludge in an anaerobic digestion process. These were compared with the results obtained from the anaerobic digestion of waste activated sludge that was not pretreated. The batch tests were carried out in both mesophilic and thermophilic conditions until the produced biogas showed variations lower than 5% (generally in 30−45 days). All data reported are net as the biogas production of the inoculum was subtracted from the total volume. Specific biogas productions (as liters of biogas produced per gram of volatile solids fed to the reactor, L/g of VS), obtained at 37 and 55 °C and converted to standard temperature and pressure (STP), are reported in Table 7; it is clear, from the data reported, that the extreme thermophilic pretreatment determined an increase in biogas production.

The increase was in the range 30−50% for the mesophilic tests and 25−48% for the thermophilic (see Figure 4). Although the results are dispersed in a wide range, it can be seen that the higher increases were obtained with a pretreatment HRT of 2−3 days.

Therefore, the application of the pretreatment step allowed an increase of the biogas yield and the production rate, to shorten the time necessary for a good stabilization.

3.3. Considerations of the Possible Application at Industrial Scale. To verify the industrial applicability of a two-stage process where the first step operates at 70 °C, the heat balance for the anaerobic digestion system operating in a hypothetical WWTP with a size of 100 000 PE was considered. The sludge production was set at 40 g per person per day, giving a TVS mass of 3200 kg/day. The resulting flow rate to the anaerobic digestion section depends on the thickening capacity of the sludge line.



IN	HRT=5d	HRT=3 d	HRT=2 d	HRT=1 d
TS, g/d	73,8	124,5	184,6	364,7
TVS, g/d	54,6	101,9	148,3	289,0
COD, g/d	67,9	107,8	166,0	317,0
dCOD, g/d	4,6	7,3	5,0	23,0
N, g/d	4,5	7,6	9,8	24,4
P, g/d	1,8	2,2	6,3	8,4

BIOGAS	HRT=5d	HRT=3 d	HRT=2 d	HRT=1 d
TS, g/d	1,7	5,8	11,0	16,8
TVS, g/d	1,7	5,8	11,0	16,8
COD, g/d	2,2	7,6	12,1	18,5

OUT	HRT=5d	HRT=3 d	HRT=2 d	HRT=1 d
TS, g/d	62,7	103,1	147,5	299,0
TVS, g/d	45,6	76,1	110,8	223,0
COD, g/d	61,5	100,7	162,0	314,1
dCOD, g/d	24,2	34,7	45,0	90,0
N, g/d	4,3	6,3	9,2	22,1
P, g/d	1,8	2,0	5,5	7,7

Figure 3. Mass balances for the extreme thermophilic anaerobic reactor.

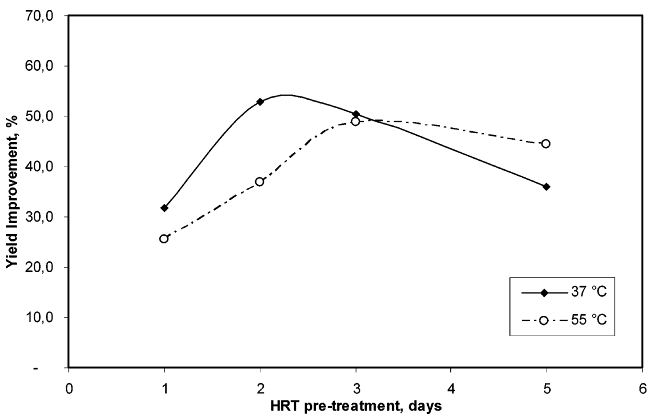


Figure 4. SGP improvement according to the HRT applied in the extreme thermophilic reactor.

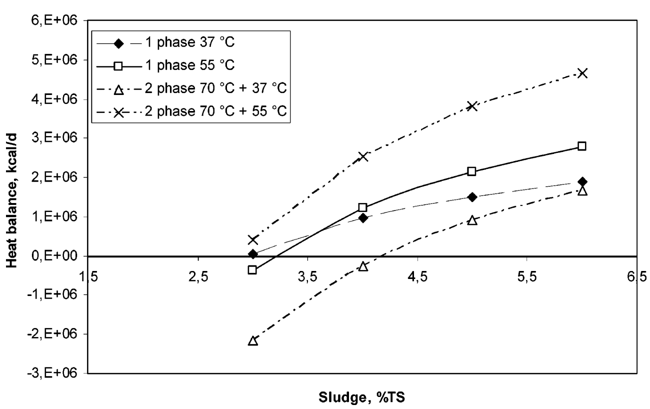


Figure 5. Heat balance for four configurations tested.

The digester volume was set at 2000 m^3 while the first stage had a volume of 200 m^3. The composition of WAS considered for calculation was the one reported in Table 3 for single-stage processes and the composition reported in Table 5 (HRT = 2 days) for the digestion of pretreated sludge in the two-stage processes, while the biogas production was the one resulting from Table 7 depending on the corresponding HRT.

With specific reference to the energetic balance, we considered the treatment of 3200 kg of TVS/day of WAS at different flow rates, depending on the solid concentration, a specific heat request of 1 kcal/kg °C, a temperature of the sludge of 12 °C, a specific biogas production as in Table 7, a combustion heat for biogas of 5500 kcal/m^3, a combustion yield of the heater of 90%, and a total heat loss from the digester walls of 10%.

Figure 5 shows the situation without (single phase) and with extreme thermophilic pretreatment: although it was the highest energy demanding, the two-phase process with a methanization step at 55 °C gave the best performances because of the increase in biogas production. On the other hand, the two-phase process with a methanization step at 37 °C showed a high energy request for the first phase while the biogas production increased only partially. The single-phase processes, at both 37 and 55 °C, gave similar results in terms of energy balance (Figure 5). In all cases the energy balance became positive for a solids content higher than 4%.

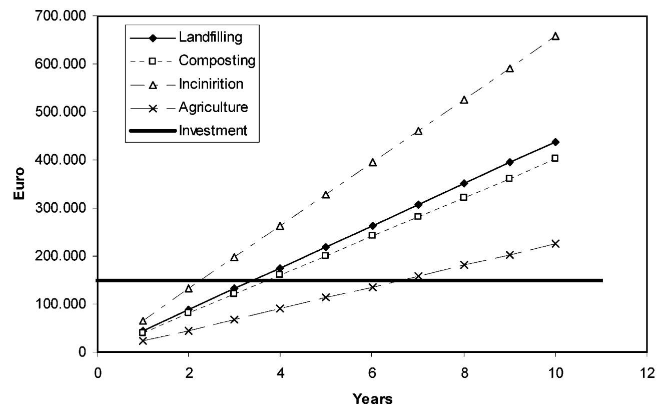


Figure 6. Pay-back time.

3.4. Economics of the Two-Phase Process. An economic balance was also carried out to evaluate the pay-back time for the investment for the realization of the first reactor operating in extreme thermophilic conditions (70 °C). Also the expenses for the adoption of the necessary heater and heat exchangers were determined according to Bolzonella et al.[28] Further, the savings deriving from the reduced production of sludge originated from the adoption of the two-stage process were also calculated.

The calculated investment for a 200 m^3 continuous reactor, complete with facilities, was determined as 150 000 euros while the savings were determined considering the reduced disposal of sludge and the average costs reported in Table 1 for different disposal options. Figure 6 shows the analytical definition of the pay-back time for the investment: here, when the line representing the expenditure for sludge disposal with a given technology crosses the investment line, then the years of pay-back time are defined. It turns out to be evident how the pay-back time is short (some 2 years) when the disposal of sludge is costly, as for incineration, while it is 6 years when disposal costs are relatively low as for sludge spreading for agricultural purposes. This is in good agreement with the findings of Boehler and Siegrist,[5] who showed that the introduction of particular pretreatment processes for the reduction of excess sludge are generally sustainable when the cost for sludge disposal is over 450 euros per ton.

4. Conclusions

A two-stage anaerobic process for the treatment of waste activated sludge, where the first step was carried out in a continuous stirred reactor operating in extreme thermophilic environment (70 °C), was studied. The following evidence was observed:

(a) The extreme thermophilic reactor determined the dissolution of up to 40% of the particulate COD in waste sludge when operating with HRTs in the range 1−5 days: typical yields were in the range 0.3−0.4 g of soluble COD per gram of volatile solids.

(b) Short-chain fatty acids (SC-VFA), from C2 to C5, were the main compounds formed in the extreme thermophilic continuous fermenter and isovalerate tended to accumulate in the reactor. This should be considered with attention as iso forms are degraded slowly compared to the normal forms of organic acids in anaerobic digesters.

(c) The hydrolysis constant at 70 °C was 0.17 day^{-1}, a value similar to those obtained under mesophilic and thermophilic conditions for mixed sludge.

(d) Batch tests for the anaerobic digestion with biogas production showed how the pretreated sludge determined better performances in terms of biogas production. The SGP showed increases in the range of 20−50% compared to the mesophilic and thermophilic single-stage tests.

(e) Economic evaluations 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 paid back in some 2−6 years, depending on the way and costs of disposal of sludge.

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Acronyms

AD = anaerobic digestion
COD = chemical oxygen demand
GPR = gas production rate
HRT = hydraulic retention time
OLR = organic loading rate
PE = people equivalent
SC-VFA = short-chain volatile fatty acids
SGP = specific gas production
TKN = total Kjeldhal nitrogen
TS = total solids
TVS = total volatile solids
VFA = volatile fatty acids
WAS = waste activated sludge
WWTP = wastewater treatment plant

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