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EFFECT OF THERMAL TREATMENT OF ANAEROBIC SLUDGE ON THE BIOAVAILABILITY AND BIODEGRADABILITY CHARACTERISTICS OF THE ORGANIC FRACTION

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Abstract - Most works reported in the literature focus on thermal treatment of waste activated sludge at temperatures in the range of 160 to 180°C. This research aimed at evaluating the thermal treatment of excess anaerobic sludge at much lower temperatures, using biogas generated in the wastewater treatment process as the energy source for heating a simplified thermal reactor. Direct burning of the biogas allowed an increase in the sludge temperature up to values close to 75°C, for a 7-hour heating period. Sludge samples taken at different heating times showed that the thermal disintegration of the organic fraction allowed increases in the concentration of protein, carbohydrate, lipid and COD parameters by 30 to 35 times, as well as a 50% increase in the biogas production. Moreover, the simplified thermal treatment system proved to be an effective alternative for recovering energy from biogas and for controlling methane emissions to the atmosphere.
Keywords: Anaerobic sludge; Bioavailability; Biodegradability; Biogas; Thermal treatment; UASB reactor.

INTRODUCTION

Although UASB reactors are considered to be a mature technology for the treatment of domestic wastewater in warm climate regions, some design and operational limitations are still present and should be addressed in order to enhance reactor performance. One limitation is related to the presence of poorly biodegradable suspended solids in the influent and, therefore, mechanisms for improving its digestion should be considered. Suspended solids correspond to around 50% of the total chemical oxygen demand (COD) of the wastewater, making hydrolysis the limiting step of the anaerobic digestion process (Foresti *et al.*, 2006). According to Metcalf & Eddy (1991), an average of 70% of the solids present in typical domestic wastewaters are of organic origin, out of which approximately 40 to 60% are protein compounds, 25 to 50% are carbohydrates and approximately 10% are fats and oils. Lower amounts of urea, surfactants, phenols, pesticides and others can also be found.

Anaerobic degradation of complex organic matter has been described as a multi-step process of reactions in which several key groups of bacteria take part (Pavlostathis & Giraldo-Gomez, 1991). The

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microorganisms cooperate sequentially in order to achieve degradation of a variety of polymeric and monomeric substrates. Digestion is initiated by the secretion of enzymes by facultative and obligate fermentative bacteria, facilitating the hydrolysis of the initial proteins and polysaccharides, including suspended organics present in domestic sewage, to monomeric sugars, amino acids, long chain fatty acids and alcohols (O'Flaherty *et al.*, 2006). According to Batstone *et al.* (2002), hydrolysis can be represented by two conceptual models: i) the organisms secrete enzymes to the bulk liquid where they are adsorbed onto a particle or react with a soluble substrate (Jain *et al.*, 1992); and ii) the organisms attach to a particle, produce enzymes in its vicinity and benefit from soluble products released by the enzymatic reaction (Vavilin *et al.*, 1996).

In order to accelerate the solubilization of the particulate organic matter, biological, chemical, physical and mechanical methods can be used, such as anaerobic digestion, aerobic digestion, thermal-chemical treatment (in either basic or acid medium), thermal treatment, ozonization (Rocher *et al.*, 1999), ultrasound, high pressure homogenizers, ball mills (Muller, 2001), humid oxidation, centrifugation (Kepp & Solheim, 2001) and chemical treatment (Deleris *et al.*, 2001), among others.

Thermal treatments were first applied to sludge to improve its dewaterability (Neyens & Baeyens, 2003), but most works deal with the effect of sludge thermal treatments on biogas production enhancement during anaerobic digestion, as summarized in Table 1. Most of the studies reported an optimal temperature in the range from 160 to 180°C and treatment times from 30 to 60 min, while thermal treatment at moderate temperature (70°C) lasted from hours to several days (Gavala *et al.*, 2003; Ferrer *et al.*, 2008; Lu *et al.*, 2008). Treatments at temperatures of 70°C or 121°C led to a 20 to 48% biogas production increase and treatments at 160–180°C led to a 40 to 100% biogas production increase. The 160–180°C pre-treatments are thus most efficient to enhance sludge anaerobic digestion, but they also lead to more dispersed results in terms of biogas production (Bougrier *et al.*, 2008). Moreover, sludge treatments at higher temperatures lead to higher investments and are largely mechanized. Thus, in order to employ these treatment principles, it is necessary to search for technologies that are suitable for the reality of developing countries, so that the sludge issue can be dealt with appropriately in these locations.

Table 1: Impact of thermal pre-treatments on primary sludge and waste activated sludge mesophilic anaerobic digestion

Reference	Thermal treatment	Anaerobic digestion	Results
Haug *et al.* (1978)	175°C, 30 min	CSTR, HRT = 15 d	Increase of CH_4 production from 115 to 186 ml/g COD_{in} (+62%)
Stuckley and McCarty (1978)	175°C, 60 min	Batch, 25 d	Increase of convertibility of COD to CH_4 from 48 to 68% (+42%)
Li and Noike (1992)	175°C, 60 min	CSTR HRT = 5 d	Increase of gas production from 108 to 216 ml/g COD_{in} (+100%)
Tanaka *et al.* (1997)	180°C, 60 min	Batch, 8 d	Increase of methane production (+90%)
Fjordside (2001)	160°C	CSTR, 15 d	Increase of biogas production (+60%)
Gavala *et al.* (2003)	70°C, 7 d	Batch	Increase of CH_4 production from 8.30 to10.45 mmol/g VS_{in} (+26%)
Barjenbruch & Kopplow (2003)	121°C, 60 min	CSTR, 20 d	Increase of biogas production from 350 to 420 ml/g VSSin (+20%)
Kim *et al.* (2003)	121°C, 30 min	Batch, 7 d	Increase of biogas production from 3657 to 4843 l/m^3 WAS_{in} (+32%)
Dohanyos *et al.* (2004)	170°C, 60 s	Batch, 20 d Thermophilic	Increase of biogas production (+49%)
Valo *et al.* (2004)	170°C, 60 min	Batch, 24 d	Increase of biogas production (+45%)
Valo *et al.* (2004)	170°C, 60 min	CSTR, 20 d	Increase of CH_4 production from 88 to 142 ml/g COD_{in} (+61%)
Graja *et al.* (2005)	175°C, 40 min	Fixed film reactor, HRT = 2.9 d	65% reduction of TSS
Bougrier *et al.* (2006a)	170°C, 30 min	Batch, 24 d	Increase of CH_4 production from 221 to 333 ml/g COD_{in} (+76%)
Bougrier *et al.* (2006b)	170°C, 30 min	CSTR, 20 d	Increase of CH_4 production from 145 to 256 ml/g VS_{in} (+51%)
Ferrer *et al.* (2008)	70°C, 9 h	Batch, 10 d	Increase of biogas production (+30%)
Lu *et al.* (2008)	70°C, 2 d	Batch, 13 d	Increase of methane production (+48%)

Source: Adapted from Bougrier *et al.* (2008)

Within this context, according to Mulder (2001), the global methane emission is estimated at 500 million tons a year and anaerobic wastewater treatment systems contribute to approximately 5% of this total, that is, about 25 million tons. Therefore, besides being strictly necessary to reduce the environmental impacts resulting from methane, whose impact is approximately twenty times higher than that of the carbon dioxide regarding the contribution to the increased greenhouse effect (Evans, 2001; IPCC, 2001), the burning of biogas can quickly reintegrate carbon into its natural cycle, thus allowing it to be used as a source of heat energy, little exploited so far.

This way, this paper seeks to evaluate the effect of the thermal treatment of anaerobic sludge on the disintegration of the remaining organic fraction. For that purpose, the increase in the bioavailability and biodegradability characteristics of organic compounds present in the anaerobic sludge was evaluated, employing the biogas generated in UASB reactors as the source of energy for heating of the sludge.

This research differs from the previous ones in various aspects: i) it deals with anaerobic sludge produced in UASB reactors; ii) it investigates the thermal treatment of sludge at much lower temperatures (below 80^{o}C); iii) it uses biogas produced in the wastewater treatment system as the energy source for heating the sludge; iv) it seeks the development a thermal treatment device that complies with the requirements of developing countries in terms of costs and operational simplicity.

MATERIAL AND METHODS

Experimental Apparatus

The pilot-scale apparatus consisted of a UASB reactor for domestic sewage treatment (main operational characteristics presented in Table 2), two biogas holders (with total storage capacity of 220 L), and a 5-liter thermal reactor. Table 3 shows the main characteristics of the experimental units, while Figure 1 shows the setup of the experimental apparatus, highlighting the biogas collecting, storage and burning systems, as well as the reactor where sludge was thermally treated.

The UASB reactor was fed with a parcel of the wastewater taken from the main sewer of Belo Horizonte – Brazil, after being submitted to preliminary treatment for sand and coarse solids removal. Each biogas holder unit was constituted of two plastic containers, one partially filled with water in order to work as hydric seal, avoiding gas leakage, and the other as a floating cover to accumulate the biogas. The thermal reactor was placed inside an insulation sleeve in order to reduce heat losses.

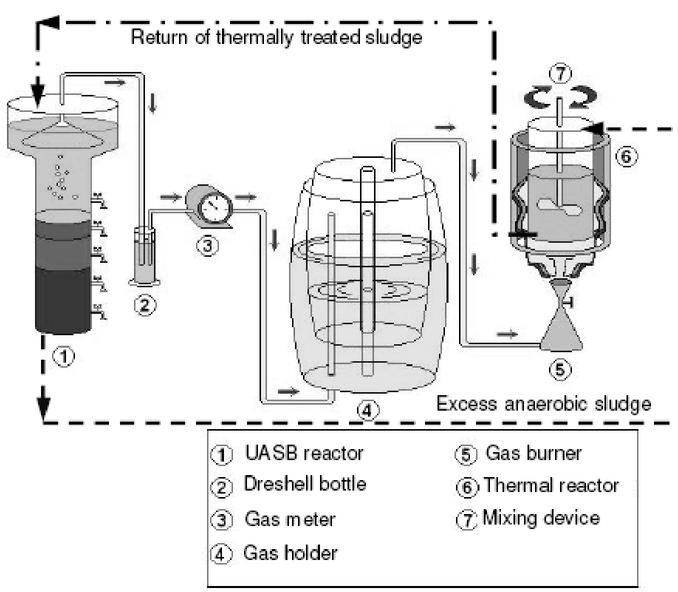

Figure 1: Set up of the experimental apparatus

Table 2: Main characteristics and operational data of the UASB reactor (average values)

Flow rate ($L.h^{-1}$)	Operating temperature (°C)	HDT (h)	Average influent COD ($mg.L^{-1}$)	Sludge concentration (%)	Biogas production ($L.d^{-1}$)	Sludge production yield ($gTS.gCOD_{applied}^{-1}$)
74	25	5.6	540	4	200	0.15

Table 3: Main characteristics of the experimental apparatus

Characteristic	UASB reactor			Biogas holder	Thermal reactor
	Digestion compartment	Settler compartment	Total		
Material	**Polypropylene**	**Fibreglass**	**-**	**Polyethylene**	**Steel**
Diameter (m)	0.30	0.30 to 0.50	-	0.50	0.15
Height (m)	3.00	1.00	4.00	0.70	0.30
Useful volume (L)	212	204	416	110	5.0

Operation of the Experimental Units

As biogas is continuously produced but excess sludge is wasted in batches, the produced biogas was stored for further burning at the time of the thermal treatment, at a final pressure between 5.5 and 6.5 cm.w.c, employing the reservatory pressure during the burning process.

The biogas volume stored and used in each test always corresponded to the 24-hour production (on average, approximately 200 $L.d^{-1}$). The volume of sludge used in each treatment experiment was determined according to the daily solids production in the UASB reactor (approximately 4.0 $L.d^{-1}$), which was estimated from the sludge yield coefficient (0.15 $gTS.gCOD_{applied}^{-1}$) and total solids concentration (average of 4.0%). The sludge was removed from the bottom of the UASB reactor and directly fed into the thermal reactor.

During the tests, the sludge was kept under constant mixing, aiming at minimizing the sedimentation of solids and the formation of a temperature gradient along the height of the thermal reactor, once the gas burner was installed under the vessel. In order to avoid mechanical rupture of the sludge particles, mixing intensity was kept at minimum level. Thermal treatment of the sludge was only initiated after homogenization and collection of a first sample. Additional samples were then collected after 1.5, 3.0, 5.0 and 7.0 hours. Only biogas was used as a source of energy and time and temperature were monitored throughout the thermal treatment process. Losses of water during the 7-hour heating period were estimated to be less than 1% of the initial sludge volume treated, because the thermal reactor was kept closed during the whole heating period.

A comparison between "samples collected at room temperature" and kept under the same stirring conditions and "samples collected after X-hours of thermal treatment" was not carried out, because samples collected at room temperature did not remain under mixing. As pointed out before, the stirring was kept at minimum level (only to avoid particle settling) and, therefore, mechanical rupture or solubilization of particulate material may not have occurred to a considerable degree. Therefore, the effect of agitation during the test period on the solubilization of the particulate matter, regardless of heat treatment, was assumed to be insignificant.

Monitoring Analyses

Aiming at evaluating the effect of the thermal treatment on the bioavailability characteristics of the sludge, filtered samples were used to quantify the COD, protein, carbohydrate and lipid contents. The COD analyses were performed according to procedures established in the Standard Methods for the Examination of Water and Wastewater (1998), whilst protein, carbohydrate and lipid analyses were performed according to Peterson (1977), Dubois *et al*. (1956), and Postma & Stroes (1968), respectively.

The effect of thermal treatment on the biodegradability of the sludge was evaluated through anaerobic tests, performed with the Oxitop® system and in accordance with the manufacturer's guidelines (WTW, 1999) and methodology presented in Borges (2004). For these tests, 20 mL of anaerobic seed sludge and 80 mL of thermally treated sludge (substrate), taken at the end of the heating period (T = 7 hours), were used. Biogas production was continuously monitored throughout the test by detecting the pressure increase inside the flasks. A blank containing sludge sample taken at time zero was also carried out. All tests were performed in duplicate, at the temperature of 30°C, and lasted for 5 days.

Statistical Tests

Statistical tests were applied for the analysis of significance between averages and variances, in order to evaluate the relationship between the changes in the concentrations of the chemical parameters and heating time and temperature variables. The tests applied were the χ^2 Test, Student's t Test, F Test, and Mann-Whitney Test. Analysis of Variance was also performed, which allows one to verify whether a given factor causes changes to a variable of interest.

Mathematical Modeling of the Results

It was noticed from plotted dispersion diagrams that each parameter/heating-time pair adjusted to a first-order reaction, specifically to an equation 1 type curve.

$$y = y_{max} - \left[\left(y_{max} - y_0 \right) \cdot e^{-k \cdot x} \right] \quad (1)$$

Because the concentration of the evaluated parameters depended on only two variables, test temperature and time, the results were mathematically modeled by taking into consideration the influence of both these variables, thus resulting in equation 2, presented as follows.

$$y = y_{max} - \left[\left(y_{max} - y_0 \right) \cdot e^{-k_{20} \cdot \theta^{(T-20)} \cdot x} \right] \quad (2)$$

where:

y = concentration of the evaluated parameter ($mg.L^{-1}$);
y_{max} = maximum concentration of the evaluated parameter ($mg.L^{-1}$);
y_0 = initial concentration of the evaluated parameter ($mg.L^{-1}$);
x = heating time (h);
T = temperature (°C);
k_{20} = reaction coefficient (h^{-1});
θ = temperature coefficient.

The non-linear regression was performed employing the Statistica/w 5.1 program for each group of results related to each parameter, with simultaneous determination of the k_{20} and θ coefficients within a 95% significance level.

RESULTS AND DISCUSSION

Effect of thermal treatment on the bioavailability characteristics

The concentrations achieved for the several parameters evaluated, followed by the heating time and temperature, at the moment at which the sample was collected, are presented in Table 4.

The results show that the concentrations of all parameters considered in the study had a positive variation from the increased heating temperature and time. For all parameters, the average variation was from 32 to 36 times between the sample collected at room temperature and the sample collected after a 7-hour thermal treatment. It is noticed that a higher efficiency was possible in the solubilization of the organic matter present in the thermally-treated sludge as the heating time and temperature were increased, suggesting that such factors have contributed for this material to become more accessible and, therefore, more available to a possible further biological degradation phase.

The differences in concentrations between samples collected at room temperature and samples submitted to thermal treatment were also confirmed by the statistical tests performed, as shown by the results of significance tests carried out for averages and variances presented in Tables 5 and 6.

In addition, the Analysis of Variance confirmed that the heating time variable had an influence on the variation of protein, carbohydrate, lipid and COD concentrations, as shown in Table 7.

An increase in dissolved COD concentration, from approximately 3,000 $mg.L^{-1}$, at the temperature of 55°C, to approximately 4,000 $mg.L^{-1}$, at the temperature of 67°C, was also achieved in the thermal treatment experiments conducted by Sorensen *et al.* (1999). Besides, França (2002) carried out thermal experiments with anaerobic sludge at similar temperatures (lower than 80°C) and observed from optical microscopic analyses (increased 100 times) the rupture of the solid fraction after the thermal treatment, which was also confirmed by the measurement of the average particle size.

Therefore, the increased quantification of the filtered fraction of proteins, carbohydrates, lipids and COD, due to the increased heating time and temperature, confirm the positive effect of the thermal treatment on the organic fraction present in the excess anaerobic sludge.

Table 4: Descriptive statistics of the protein, carbohydrate, lipid and COD parameters

Heating time (hour)		0.0	1.5	3.0	5.0	7.0
Number of samples		10	10	10	10	10
Temperature (^{0}C)	Mean	25.1	49.8	63.6	72.0	74.1
	Maximum	29.5	56.5	72.5	76.0	77.5
	Minimum	22.0	45.0	57.0	66.0	70.0
	Standard Deviation	2.80	3.81	4.76	2.94	2.40
	Increase (N^o of times)	-	-	-	-	-
Proteins (mg.L^{-1})	Mean	86	1051	2081	2610	2829
	Maximum	124	2332	3463	3413	3463
	Minimum	55	323	1241	1746	1959
	Standard Deviation	19	637	698	537	445
	Increase (N^o of times)	-	12	24	30	33
Carbohydrates (mg.L^{-1})	Mean	22	208	559	709	795
	Maximum	37	701	968	1056	1184
	Minimum	12	46	303	502	611
	Standard Deviation	7	192	174	163	170
	Increase (N^o of times)	-	9	25	32	36
Lipids (mg.L^{-1})	Mean	0.06	0.55	1.16	1.70	1.83
	Maximum	0.13	1.41	2.18	2.44	2.44
	Minimum	0.02	0.28	0.66	1.24	1.41
	Standard Deviation	0.03	0.33	0.41	0.38	0.35
	Increase (N^o of times)	-	10	21	31	33
COD (mg.L^{-1})	Mean	217	2073	4103	6059	7053
	Maximum	305	3287	5501	7447	8050
	Minimum	160	1003	1800	4223	4999
	Standard Deviation	53	860	1042	1084	893
	Increase (N^o of times)	-	10	19	28	32

Table 5: Summary of significance tests between averages of samples collected at time 0 (T0.0h) and after 7.0 hours of thermal treatment (T7.0h) - (Test t Student)

Parameters	Significance level	t (calculated)	t (table)	H_0	Conclusion
Proteins (T0.0h – T7.0h)	$\alpha = 0.05$	-18.48	2.1	Reject	$\mu_1 \neq \mu_2$
Carbohydrates (T0.0h - T7.0h)	$\alpha = 0.05$	-13.64	2.1	Reject	$\mu_1 \neq \mu_2$
Lipids (T0.0h – T7.0h)	$\alpha = 0.05$	-15.29	2.1	Reject	$\mu_1 \neq \mu_2$
COD - T0.0h - T7.0h	$\alpha = 0.05$	-22.92	2.1	Reject	$\mu_1 \neq \mu_2$

Table 6: Summary of significance tests between variances of samples collected at time 0 (T0.0h) and after 7.0 hours of thermal treatment (T7.0h) - (Test F)

Parameters	Significance level	F (calculated)	F (table)		H_0	Conclusion
			Lower	Higher		
Proteins (T0.0h - T7.0h)	$\alpha = 0.05$	0.0017	0.25	4.03	Reject	$S_1^2 \neq S_2^2$
Carbohydrates (T0.0h - T7.0h)	$\alpha = 0.05$	0.0016	0.25	4.03	Reject	$S_1^2 \neq S_2^2$
Lipids (T0.0h - T7.0h)	$\alpha = 0.05$	0.0098	0.25	4.03	Reject	$S_1^2 \neq S_2^2$
COD (T0.0h – T7.0h)	$\alpha = 0.05$	0.004	0.25	4.03	Reject	$S_1^2 \neq S_2^2$

Table 7: Summary of Analysis of Variance (ANOVA)

Dependent variable	Indenpendent variable	F (calculated)	F (table)	H_0	Conclusion
Protein concentration	Heating time	47.74	2.59	Reject	The independent variable affects each dependent variable
Carbohydrate concentration	Heating time	44.93	2.59	Reject	
Lipid concentration	Heating time	27.61	2.88	Reject	
COD concentration	Heating time	103.74	2.59	Reject	

Effect of Thermal Treatment on Sludge Biodegradability

Thermal treatment had a very positive effect on sludge anaerobic biodegradability, as confirmed by the increment in biogas production, which was 50% higher for the sludge samples collected after 7.0 hours of thermal treatment, as compared to samples taken at time zero and therefore not submitted to thermal treatment (Table 8 and Figure 2).

These results are in agreement with those presented in Table 1, where it can be noticed that sludge treatments at temperatures of 70°C or 121°C led to a 20 to 48% increase in biogas production. However, most of the results presented in Table 1 are related to thermal treatment of sludges originated from activated sludge treatment plants (primary, secondary or mixture of primary and secondary sludges), while sludge originated from an UASB reactor treating domestic wastewater was used in the present work.

Mathematical Modeling of the Results

The influence of temperature and heating time on the characteristics of the anaerobic sludge submitted to thermal treatment was modeled according to Equation 2. The coefficients and variables obtained from this model are presented in Table 9.

In equations that seek to model first-order reactions, the k coefficient is associated with the organic matter degradation rate. The higher its value, the higher is the organic matter oxidation rate. In the results analyzed herein, specifically for the protein, carbohydrate, lipid and COD parameters, it is understood that the organic matter bioavailability rate can be analyzed from the k coefficient, present in mathematical equation 2. As can be seem from the k_{20} coefficient values presented in Table 9, a higher organic matter bioavailability rate is noticed for the carbohydrate parameter. Regarding the determination coefficients (R^2) for the referred to parameters, good correlations (varying from 0.82 to 0.90) can be noticed between the variation in their concentration and the heating time and temperature variables.

The temperature coefficient θ, based on the Van't Hoff-Arrhenius theory, seeks to characterize the influence of temperature on the reaction rate at issue. The higher the θ value, the higher is the influence of temperature on the reaction and, consequently, the higher is the influence of temperature on the bioavailability rates of the organic matter present in the sludge submitted to thermal treatment. As can be noticed from the θ coefficient values presented in Table 9, a higher influence of the temperature variation was also observed for the carbohydrate parameter ($\theta = 1.066$). For the other parameters, the temperature coefficient varied from 1.013 to 1.058, also confirming that the thermal treatment contributed positively to the increased bioavailability of the organic matter present in the sludge being treated.

Table 8: Tests of anaerobic biodegradability - Summary of descriptive statistic results

Heating time (hour)		**0.0**	**7.0**
Biogas production (mL)*	Mean	**312**	**468**
	Maximum	437	627
	Minimum	139	387
	Standard Deviation	155	137
Variation (%)		0	50

*Biogas volumes refer to measurements taken after 5 days of test.

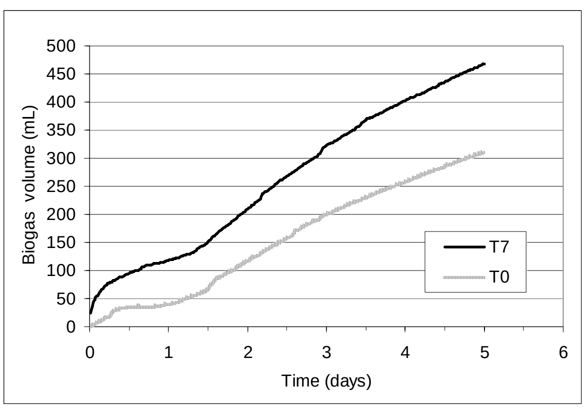

Figure 2: Biogas production during the anaerobic biodegradability tests (average results - T0: sludge sample collected at time 0; T7: sludge sample collected after 7 hours of thermal treatment).

Table 9: Coefficients and variables obtained for the protein, carbohydrate, lipid and COD parameters, from the mathematical model applied

Mathematical model: $y = y_{max} - \left[(y_{max} - y_0) \times e^{-k_{20} \times \theta^{(T-20)} \times x} \right]$		
Coefficient / Variable		**Value**
Proteins	y_{max} (mg.L^{-1})	2815.0
	Y_0 (mg.L^{-1})	91.8
	k_{20} (h^{-1})	0.0997
	θ	1.035
	R^2	0.82
Carbohydrates	y_{max} (mg.L^{-1})	782.2
	Y_0 (mg.L^{-1})	25.3
	k_{20} (h^{-1})	0.2404
	θ	1.066
	R^2	0.84
Lipids	y_{max} (mg.L^{-1})	1.87
	Y_0 (mg.L^{-1})	0.10
	k_{20} (h^{-1})	0.0272
	θ	1.058
	R^2	0.86
COD	y_{max} (mg.L^{-1})	8587.3
	Y_0 (mg.L^{-1})	164.6
	k_{20} (h^{-1})	0.1216
	θ	1.013
	R^2	0.90

k_{20} and θ coefficients were determined within a 95% significance level

Figures 3 to 10 present adjustment curves for the parameters evaluated, related separately to the heating time and temperature variables. For the evaluated parameter/heating-time pair, the position of the dots was similar to the equation 1 type curve, as previously presented, and the adjustment was then made to this equation model. The position of the dots for the evaluated parameter/heating-temperature pair suggested an exponential curve ($y = a.b^x$; Spiegel, 1993), which shows the model of a curve with a first-order reaction rate, according to equation 3.

$$y = y_0 \cdot e^{(k \cdot x)} \tag{3}$$

The results seem to indicate that the variations in the concentrations are more sensitive to increases in temperature rather than to increases in heating time. A smaller influence of the heating time variable in relation to temperature during the thermal treatment process was also reported by Muller (2001). Bougrier *et al.* (2008) found a major effect on the solubilization of COD, protein, carbohydrate, protein and of the solid fraction as the temperature was varied from 20^{o}C to 210^{o}C, however for sludge thermal pre-treatment carried out at similar heating time intervals. The use of high temperatures and short heating periods during the thermal hydrolysis of organic compounds has also been reported by various authors (Haxaire *et al.,* 2000; Schieder *et al.,* 2000; Weiz *et al.,* 2000; Dohanyos *et al.,* 2004; Graja *et al,* 2005; Bougrier *et al.,* 2008). On the other hand, works carried out at lower temperatures and extended time periods can be characterized as either mesophilic (30 to 38^{o}C, period of days) or thermophilic (49 to 57^{o}C, period of days) sludge anaerobic digestion, rather than to processes of thermal disintegration of the organic fraction (Metcalf & Eddy, 1991).

These results also allow consideration of the hypothesis that, by continuing to increase the temperature, the higher will be the degree of thermal disintegration of the organic fraction and, consequently, the higher will be the increments in the bioavailability and biodegradability characteristics of the thermally-treated sludge. This is in agreement with works that report the optimal treatment temperature to reach thermal disintegration of organic compounds ranging from 160 to 180^{o}C (Haug *et al.*, 1978; Stuckley and McCarty, 1978; Li and Noike, 1992; Tanaka *et al.*, 1997; Fjordside, 2001; Dohanyos *et al.*, 2004; Valo *et al.*, 2004; Valo *et al.*, 2004; Graja *et al.*, 2005; Bougrier *et al.*, 2006a; Bougrier *et al.*, 2006b; Bougrier *et al.*, 2008).

$$Y = 3297.26 - \left[(3297.26 - 37.54) \times 2.718^{-0.2972X} \right]$$

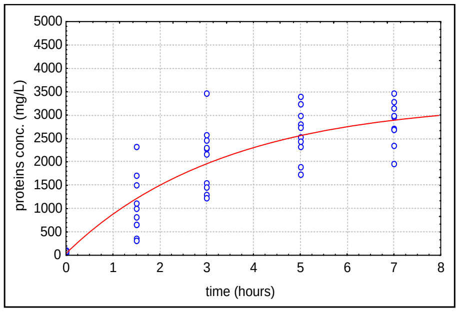

Figure 3: Adjustment curve – protein concentration and heating time.

$$Y = 147.959 \times 2.718^{(0.0398X)}$$

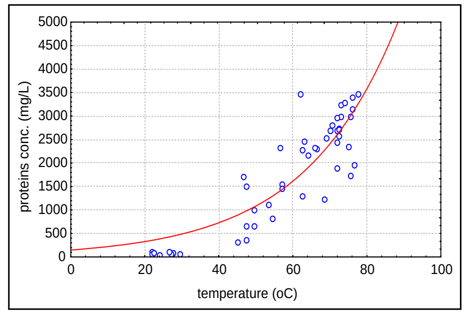

Figure 4: Adjustment curve – protein concentration and heating temperature.

$$Y = 1042.86 - \left[(1042.86 - 4.58) \times 2.718^{-0.2191X} \right]$$

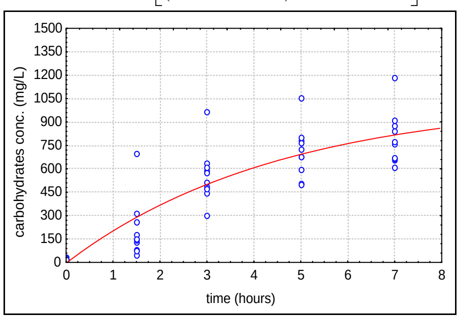

Figure 5: Adjustment curve – carbohydrate concentration and heating time.

$$Y = 17.788 \times 2.718^{(0.0515X)}$$

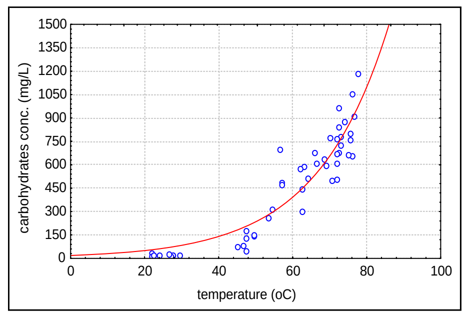

Figure 6: Adjustment curve – carbohydrate concentration and heating temperature.

$$Y = 2.532 - \left[(2.532 - 0.011) \times 2.718^{-0.1977X} \right]$$

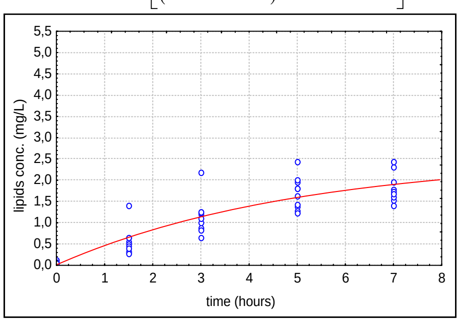

Figure 7: Adjustment curve – lipid concentration and heating time.

$$Y = 0.043 \times 2.718^{(0.0508X)}$$

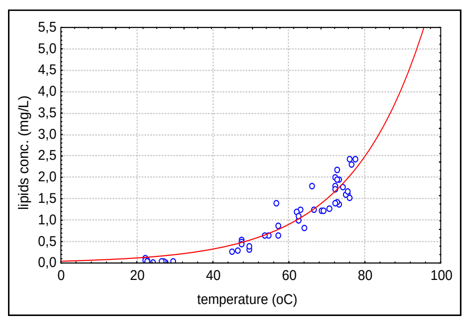

Figure 8: Adjustment curve – lipid concentration and heating temperature.

$$Y = 10932.6 - \left[(10932.6 - 114.8) \times 2.718^{-0.1511X} \right]$$

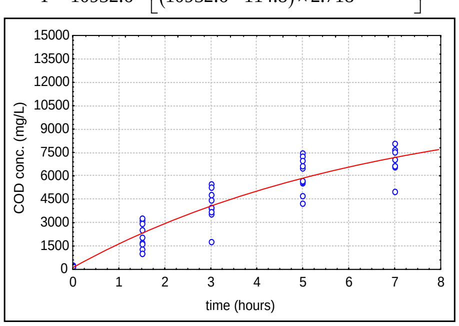

Figure 9: Adjustment curve – COD concentration and heating time.

$$Y = 256.238 \times 2.718^{(0.0438X)}$$

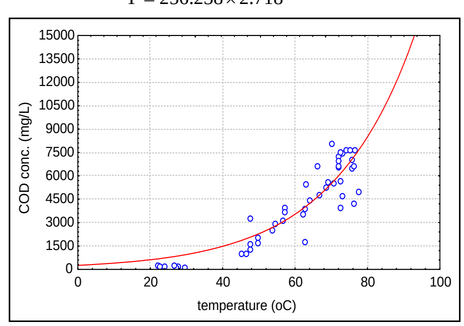

Figure 10: Adjustment curve – COD concentration and heating temperature.

CONCLUSIONS

The use of the biogas generated in UASB reactors was shown to be a self-sustainable source of energy for the thermal treatment of excess sludge, allowing an increase in the sludge temperature up to values close to 75°C, for 7-hour heating times. These ranges of temperature and heating times were sufficient to promote:

- The thermal disintegration of the organic fraction present in the anaerobic sludge submitted to the treatment;
- Statistically significant improvements in the bioavailability characteristics of the organic fraction present in the sludge, with the increased bioavailability following a first-order reaction rate;
- An increase of 30 to 35 times in the concentrations of protein, carbohydrate, lipid and COD, thus characterizing a higher bioavailability of the remaining organic fraction.
- An increase of 50 % in the biogas production, thus characterizing a higher biodegradability of the remaining organic fraction.

Overall, the simplified system was very effective for the thermal treatment of the anaerobic sludge produced in the UASB reactor, although it has been achieved at low temperatures and at atmospheric pressure. Furthermore, the system allowed the use of the biogas produced within the treatment plant, being therefore an effective alternative for recovering energy from biogas and for controlling methane emissions to the atmosphere.

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