Anaerobic Mesophilic and Thermophilic Municipal Sludge Digestion

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In this study the performance of mesophilic and thermophilic anaerobic digestion of sludge at pilot-scale, have been presented.

The thermophilic reactor was operated at solids retention time between 75–20 days, while the mesophilic process was operated at 27 days. Evaluation of performance was in terms of a number of quantities including: OLR removal (as kg m^{-3} d^{-1} VS and kg m^{-3} d^{-1} COD), methane generation (as m^3 kg^{-1} CH_4 in the VS_r), individual volatile fatty acids (VFAs) generation, and total acidity.

Experimentally it was confirmed that the maximum loading rate achieved was 1.87 kg m^{-3} d^{-1} VS and 3.12 kg m^{-3} d^{-1} COD (at SRT: 20 days) for the themophilic process. Under these conditions, the volatile solids removal efficiency and organic removal efficiency was 38.0% VS_r and 24.7 % COD_r respectively, and the methane generation was 0.24 m^3 kg^{-1} CH_4 in the VS_r.

At SRT 27 days and mesophilic conditions, the organic loading rate removal was 0.69 kg m^{-3} d^{-1} VS_r and 1.37 kg m^{-3} d^{-1} COD_r and the methane generation was 0.40 m^3 kg^{-1} CH_4 in the VS_r. At the same SRT, the thermophilic process operated with 0.80 kg m^{-3} d^{-1} VS_r and 0.96 kg m^{-3} d^{-1} COD_r organic loading rate removal, and the methane generation was 0.24 m^3 kg^{-1} CH_4 in the VS_r.

The experimental results showed, that with 27 days retention time there was little difference in the VS removal efficiency by two types of processes at organic loading rates (OLR) up to 1.3 kg m^{-3} d^{-1} VS. However, at low SRT, the thermophilic reactor produced more gas than the mesophilic at OLR up to 2.19 kg m^{-3} d^{-1} COD.

Keywords:
Anaerobic digestion, mesophilic, thermophilic, sludge, solids retention time, VFA.

Introduction

The disposal of sludge continues to be one of the most difficult and expensive problems in the field of wastewater engineering. Municipal sludge quantities have increased in recent past, but the options for municipal sludge disposal have been severely restricted due the regulations enacted to protect the environment. The importance of municipal sludge disposal is further emphasized when economic considerations are taken into account.

Anaerobic digestion has been and continues to be one of the most widely used processes for the stabilisation of wastewater treatment plant sludge. The complexity of anaerobic digestion arises from process sensitivity and interactions of components that make up the complete system.[1]

The sizing of anaerobic digesters is based on providing sufficient sludge residence to allow significant volatile solids destruction to occur. The SRT (or HRT) and the extent of each of the three reactions occurring during anaerobic digestion (hydrolysis, acid formation and the methane formation) are directly related. An increase in SRT increases the extent of each reaction; a decrease in SRT decreases the extent of reaction. There is a minimum SRT for each reaction; if the SRT is less than the minimum SRT, bacteria cannot grow rapidly enough to remain in the digester, the reaction mediated by those bacteria will cease and the digestion process will fail.[2] However, anaerobic digestion of "typical" domestic wastewater sludge has been sufficiently characterised such, that the designer normally does not need to consider the microbiology of the process in detail.

Temperature is important in determining the rate of digestion, particularly rates of hydrolysis and methane formation. The design operating temperature establishes the minimum SRT (or HRT) required to achieve a given amount of volatile solids destruction[1]. Most digesters, of whatever configura-

*Author to whom the correspondence will be addressed tion, tend to be operated in the mesophilic temperature range (30–35 °C). Some system have been designed to operate in the thermophilic temperature range (approximately 55 °C). Disadvantages claimed for the thermophilic digestion include the higher operating costs, lower process stability, and more structural requirements. Advantages related to the thermophilic digestion include improved sludge dewaterability, increased pathogen destruction and increased scum digestion.

The direct comparisons of the performance of thermophilic and mesophilic digester in the literature show a degree of confusion.[1,2] *Harris* and *Dague*[3] showed that, with a long retention time, there was little difference in the gas produced by two types of digester at organic loading rates (OLR) up to 20 kg m^{-3} d^{-1} COD. However, a low HRT, the mesophilic reactor produced less gas than the thermophilic at OLR range 5.5–13.75 kg m^{-3} d^{-1} COD. On the other hand, the work of *Dinsdale* et al.[4,5] showed that the maximum OLR that could be maintained by a thermophilic UASB was only marginally higher than that for a mesophilic UASB.

The purposes of this study was to investigate the influence of SRT on the performance and treatment efficiency (based in COD and VS removal) of sludge digestion in a pilot digester, which decomposes municipal sludge at thermophilic conditions (55 °C), and to compare the performance of digester at mesophilic conditions.

Materials and methods

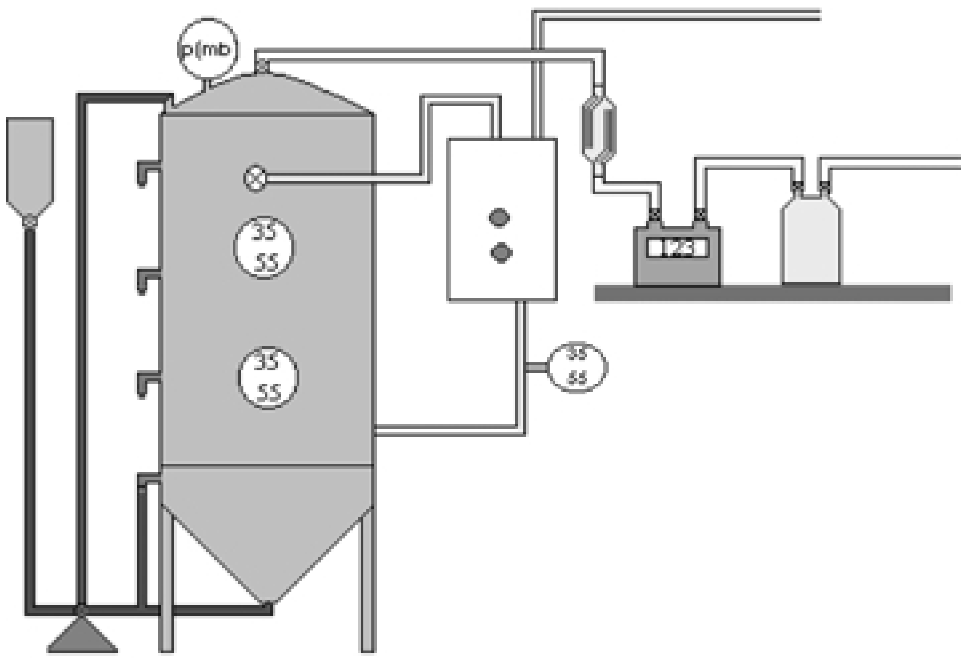
Description of pilot digester

The completely mixed anaerobic digester (CSTR, continuously stirred tank reactor) used in this study, as illustrated in Figure 1, was 150 L in net volume of the column with a cross-section of 1 100 cm^2 and 165 cm of length. The process temperature was controlled at 35 °C and 55 °C, respectively, for the mesophilic and thermophilic experiments by applying recirculation of temperature controlled water through the double wall of the reactor.

The digester was initially re-start-up and inoculated with a digested mesophilic sludge (containing 17.14 g L^{-1} VS) from Guadalete Wastewater Treatment Plant (WWTP), placed in Jerez de la Frontera (Cadiz-Spain), which is a conventional municipal wastewater treatment plant. At mesophilic conditions and SRT 27 days, the digester was operated for about tree months.

After this, the temperature of digester was increased to 55 °C. The strategy selected for converting from mesophilic to thermophilic digestion was the slow gradual temperature increase employed by *Rimkus* et al.[6] in Chicago.

The feeding consisted of a raw sludge (mixture of primary and activated sludge) from the aforementioned WWTP. Three times per day, a certain volume of digested sludge was withdrawn from the reactor (depending of the SRT imposed), and an



F i g . 1 – *Schematic diagram of pilot plant digester used in this study* equal volume of raw sludge was pumped into the recycle line of the digester.

The effluent from the digester was recycled. Recycle flow rate (50 L h^{-1}) was drawn at the bottom of the reactor and pumped through a variable speed centrifugal pump at the top of the reactor in order to maintain the mixed conditions into digester.

Sampling and analysis

Quantities measured were: chemical oxygen demand (COD), total solids (TS_0, TS_e) and volatile solids (VS_0, VS_e) of influent and effluent, pH, bicarbonate alkalinity, gas production, composition of gas (methane and carbon dioxide fraction), individual volatile fatty acids (VFAs), and concentration of methanogenic bacteria.

All analytical determinations were performed according to "Standard Methods".[7]

Gas produced was collected in 50 L gas-meter filled with acidified saturated salt solution. Biogas samples were periodically obtained from gas meter. A gas sampling valve was installed at the top of the collector to allow direct gas sampling with a syringe. The volume of gas produced in the reactor was directly measured by a mass flow-sensor while gas composition (methane and carbon dioxide) was carried out by gas chromatography separation (SHIMADZU GC-14 B) with a stainless steel column packed with Carbosive SII (diameter of 3.2 mm and 2 m length) and thermal conductivity detector (TCD). The injected sample volume was 1 cm^3 and operational conditions were as follows:[8,9] 7 min. at 55 °C; ramped at 27 °C min^{-1} until 150 °C; detector temperature: 255 °C; injector temperature: 100 °C. The carrier was helium and the flow rate used was 30 ml min^{-1}. A standard gas (by Carburos Metálicos, S.A; composition: 4.65 % H_2; 5.33 % N_2; 69.92 % CH_4 and 20.10 % CO_2) was used for the calibration of the system.

Concentrations of individual VFA levels in effluent were determined by a gas chromatograph (SHIMADZU GC-17 A) equipped with a flame--ionisation detector and a capillary column filled with Nukol (polyethylene glycol modified by nitroterephthalic acid). The temperature of the injection port and detector were 200 °C and 250 °C, respectively. Helium was the carrier gas at 50 mL min^{-1}. In addition, nitrogen gas was used at 30 mL min^{-1} flow rate. Total VFA was calculated as addition of individual VFA levels.

Methanogenic bacteria concentration were determined by using epyfluorescence microscopy with length wave excitation at 400–440 nm and with barrier filter at 460 nm. (based in the methodology proposed by *Doddema* and *Vogels*[10], *Jain*[11], and *Solera*[12]).

Reactor operation

The study was conducted in a pilot-scale digester placed in Guadalete WWTP using digested mesophilic sludge (containing 17.14 g L^{-1} VS) as inoculum and raw sludge as feed.

The main characteristics of feed used are summarised in Table 1.

Table 1 – *Main characteristics of raw sludge*

Quantities	Maximum Value	Minimum value	Mean value
COD, mg L^{-1}	102.2	36.0	71.7
pH	6.33	5.45	5.94
Total Solids, g L^{-1}	78.62	30.18	51.43
Volatile Solids, %	73.53	51.93	67.81
Volatile Solids, g L^{-1}	46.48	22.22	34.80

At first, the digester was fed with raw sludge (by combined primary and secondary sludge of the plant) containing 55 g L^{-1} TS and 39 g L^{-1} VS and pH 6.1, at strength of 31.5 kg m^{-3} to give an organic loading rate of 0.42 kg m^{-3} d^{-1} VS with a SRT of 75 days. After this, hydraulic retention time was gradually decreased, remaining constant during each stage, until reaching the steady-state conditions. The attainment of the steady state was verified after an initial period (three times the HRT) by checking whether the constant effluent characteristic values (VS removal, COD removal and methane generation) were the mean of the last measurements in each stage. Sodium carbonate was added at concentration of 2 mol L^{-1} to maintain the digestion at the optimum pH for anaerobic thermophilic digestion.

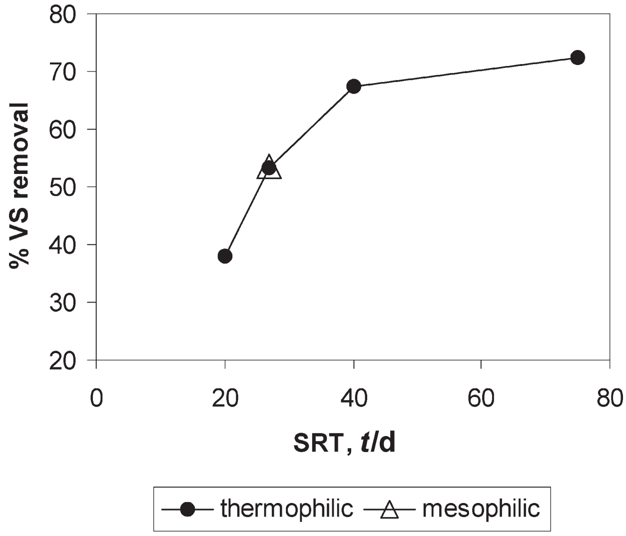
Fang and *Chui*[13] reported that the COD removal efficiency was mainly dependent on the COD loading rate, and was not sensitive to either the hydraulic retention time or the wastewater COD level alone. In this study, COD loading rate was increased by reducing SRT which was kept within 75–20 days and by adjusting the feed COD (depending to the daily mixture of sludge in the plant).

At mesophilic conditions the digester operated at 27 days detention time in order to reproduce the operation conditions imposed in industrial reactor of Guadalete WWTP.

Results and discussion

The progress of the digestion was determined by monitoring COD and VS reduction, gas production and gas composition, pH and individual VFA levels at each detention times (ranging from 75 days to 20 days at thermophilic conditions and 27 days for the mesophilic operation). Data used are averaged over minimum of three retention times of operation.

COD and volatile solids reduction are commonly used to measure the performance of anaerobic digestion processes. Figure 2 illustrates the relationship between VS removal efficiency at each SRT studied at thermophilic and mesophilic conditions.



F i g . 2 – *Evolution of Volatile Solids reduction (as %VS_r) at each SRT studied*

The design operating temperature establishes the minimum SRT required to achieve a given amount of volatile solids destruction. At mesophilic conditions and industrial scale, 40 % volatile solids reduction is an acceptable value in the performance of sludge digestion process[13]. Total and volatile solids reduction were always higher in the thermophilic unit when the SRT was upper than 27 days (above 53 % VS_r). Nevertheless, when the SRT was lower than 27 days, the efficacy of the thermophilic process dropped sharp until 38 % VS_r (at SRT 20 days).

At 27 days solids retention time, the efficiency of both systems was the same (53 % volatile solids reduction). At full scale, this efficiency is acceptable.[14]

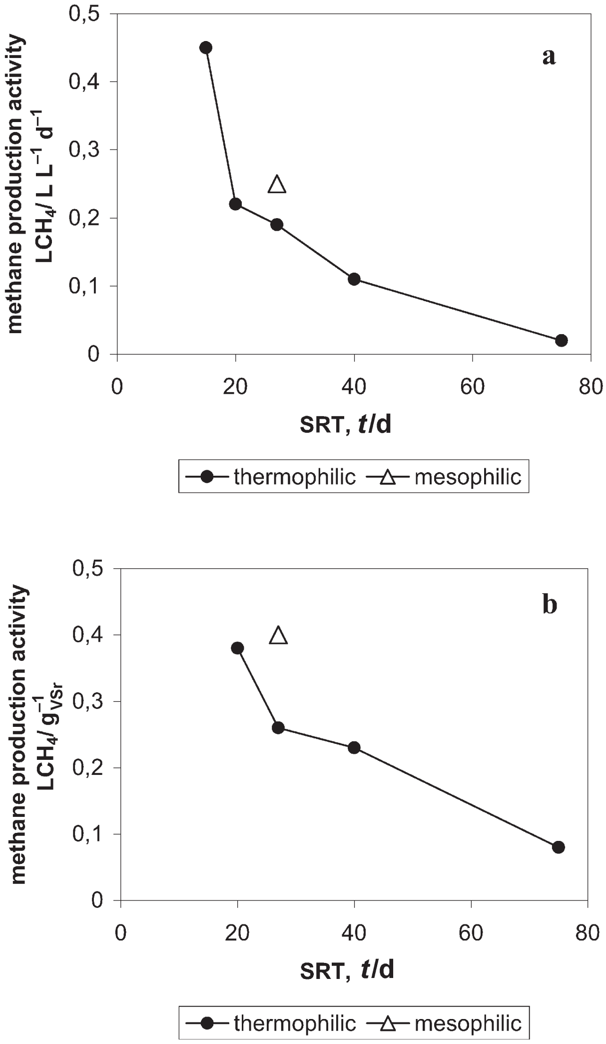
The COD removal of the mesophilic sludge was higher than that of the thermophilic sludge at 27 days solids retention time (52.8 % COD_r vs 35.3 % COD_r).

The daily gas production and gas composition was monitored in all stages of the mesophilic and thermophilic digester. Gas production was always similar in the two units, with mesophilic production only slightly higher than thermophilic production (0.31 m^3 m^{-3} d^{-1} vs 0.36 m^3 m^{-3} d^{-1} at t_{SRT} = 27 d).

In all cases, methane fraction in each unit averaged close to 60 %, ranging from 57.7 % to 64.5 %. The operation of both units based on these traditional parameters was normal.

The influence of SRT on volumetric methane rate production are shown in Figure 3 a. As would be expected, the volumetric methane increased with decreasing SRT. At thermophilic conditions, methane gas production averaged 0.02 and 0.22 m^3 m^{-3} d^{-1} at SRT of 75 and 20 days respectively.

It has often been suggested that operation at thermophilic temperatures will provide better breakdown of organics and, consequently, more methane. However, at 27 days solids retention time, methane rate production of the mesophilic digester was consistently higher than that of the thermophilic unit (0.25 m^3 m^{-3} d^{-1} vs 0.19 m^3 m^{-3} d^{-1}).



F i g . 3 – *Influence of SRT on: a) volumetric methane rate production (m^3 m^{-3} d^{-1} CH_4) and b) methane production activity (as m^3 of methane produced per gram of VS removal)*

Similarly (see Figure 3 b), methane production activity (as m^3 of methane produced per gram of VS removal) of the mesophilic system was clearly superior to the thermophilic unit, 0.40 m^3 kg^{-1} CH_4 in the VS_r and 0.24 m^3 m^{-3} CH_4 in the VS_r, respectively.

The individual VFA levels (acetate, propionate, C-4 and total VFA, as mg L^{-1}) in the effluent of the thermophilic and mesophilic reactor from each operation reactor stage is shown in Table 2. As can be seen, at thermophilic conditions, the total VFA increased between 5 500 and 6 400 mg L^{-1} when the SRT decreased from 40 to 20 days. C-4 concentrations (butyric and isobutyric acids) increased during all the stable process, showing that no dramatic changes occur with SRT when SRT was longer than 20 days (range 300–450 mg L^{-1}). The mesophilic volatile acid concentrations were always in the range of 100–500 mg L^{-1}.

Table 2 – *Individual VFA levels (acetic acid, propionic acid, C-4 and total VFA, as mg L–1) in the effluent.*

SRT	T	Acetic	Propionic	C4	Total acidity
days	°C	γ / mg L^{-1}	γ / mg L^{-1}	γ / mg L^{-1}	γ / mg L^{-1}
75	55	3527	1458	241	5532
40	55	1858	1880	353	5379
27	55	1473	2100	512	5688
27	35	515	103	109	830
20	55	1133	2424	421	6432

One of the major criticisms about the use of thermophilic digestion is that the final effluents contain higher concentrations of volatile fatty acids than those from mesophilic digester. The data here support this supposition (at 27 days SRT, total acidity was 5 688 mg L^{-1} at thermophilic conditions vs 830 mg L^{-1} at mesophilic conditions). Thus, the individual VFA levels were consistently lower than those of the thermophilic unit in all SRTs studied. However, stable performance of digester was observed in all stages of the thermophilic study.

Raw sludge pH ranged from 5.4 to 5.8, alkalinity from 600 to 2100 mg L^{-1} and volatile acids from 600 mg L^{-1} to 2100 mg L^{-1}, which are typical values[15].

Thermophilic sludge pH was kept at constant level of 7.7–7.8, while mesophilic sludge pH was maintained over 7.5. Thermophilic bicarbonate alkalinity was also slightly higher than the mesophilic alkalinity, 14 000 mg L^{-1} $CaCO_3$ vs 12 500 mg L^{-1} $CaCO_3$ at t_{SRT} = 27 d. The high alkalinity level indicate that the various bacterial groups are in balance.

The ac/alk mass ratio (m_{AcOH}/m_{CaCO3}) decreased with SRT until stabilisation was reached in constant values in the range 0.25–0.30 mg mg^{-1} (very high for the operation at thermophilic conditions.)[16] Therefore, thermophilic digestion of municipal sludge could be established at 3.12 kg m^{-3} d^{-1} COD (20 days) with the addition of sodium carbonate, Na_2CO_3.

When the SRT was 27 days, mesophilic ac/alk mass ratio was very low, 0.065 vs 0.350 at thermophilic conditions. However, the thermophilic digester showed stable operation in all stages of the study.

Conclusions

The results obtained here indicated no advantage to operation of anaerobic thermophilic temperatures, when the SRT was 27 days or upper, as indicated by total and volatile solids breakdown and by gas production. However, when the SRT was lower than 27 days, the thermophilic process was significantly better, as indicated by gas and methane generation.

Thereby, at SRT 27 days, the mesophilic organic loading rate removal was 0.69 kg m^{-3} d^{-1} VS and 1.37 kg m^{-3} d^{-1} COD and the methane generation was 0.40 m^3 kg^{-1} CH_4 in VS_r. At the same SRT, the thermophilic process operated with 0.80 kg m^{-3} d^{-1} VS and 0.96 kg m^{-3} d^{-1} COD organic loading rate removal, and the methane generation was 0.24 m^3 kg^{-1} CH_4 in VS_r.

Therefore, the experimental results showed, that with 27 days retention time there was little difference in the VS removal efficiency by two types of processes at organic loading rates (OLR) up to 1.3 kg m^{-3} d^{-1} VS. However, at low SRT, the thermophilic reactor produced more gas than the mesophilic at OLR up to 2.19 kg m^{-3} d^{-1} COD.

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Abbreviations and symbols

COD – Chemical Oxygen Demand
COD_r – Chemical Oxygen Demand removal
HRT – Hydraulic Retention Time
OLR – Organic Load Rate
OLR_r – Organic Load Rate removed
OLR_0 – Initial Organic Load Rate
SRT – Solids retention time
TS_0 – Initial Total Solids
TS_e – Effluent Total Solids
VS – Volatile Solids
VS_0 – Initial Volatile Solids
VS_e – Effluent Volatile Solids
VS_r – Volatile Solids removal
VFA – Volatile fatty acids
m – Mass
t – Time

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