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Efficiency of Anaerobic Digestion of Low-Strength Sludge under Different Thermophilic Conditions

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Abstract: This study reports the efficiency of the anaerobic process for digestion of low-strength domestic sewage sludge under different thermophilic conditions. The efficiency was assessed in terms of methanogenic activity along the experimental period as well as the maximum reduction of organics pollutants in the investigated sludge samples. The experimental work was conducted in a batch system under different temperatures (40, 45, 50°C) to ascertain the optimum condition for the degradation process. The results show a removal efficiency of 81% of COD, 96% of BOD and 74% of TS within about 52 days of inoculation under 40°C. Only a slight increase in removal performance was observed with the increase of operating temperature. The period required for complete digestion was also observed to be temperature independent. The M-Factor (COD removed into methane/COD removed) ranged around 0.25 irrespective of the operational temperature. Irrespective of the operating temperature, the maximum methanogenic activity was delayed until 52 days. In accordance with the observed resnlts, it is suggested that the anaerobic digestion process should be designed according to the maximum methanogenic activity (gCOD-CH_4/gVSS/day) and the corresponding required digestion time (days), which, in turn, depend on the composition and characteristics of sludge.

Key words: Sludge stabilization, anaerobic digestion, methane production, operating temperature, organic matter

INTRODUCTION

The treatment of domestic and industrial wastewater results in the production of sludge that has undesirable, harmful characteristics. This sludge needs to be further processed to enable its safe disposal or reuse. Such process is commonly called stabilization or digestion. Sludge stabilization has been practiced for over 100 years and the associated cost represents a major part of the total cost in any wastewater treatment plant (Vessilind *et al*., 1988; Cheremisinoff, 1994; Pierkiel and Lanting, 2005). There is, however, lack of consensus over the sludge disposal standard. For instance, according to the sludge disposal guidelines prepared by the Concerted Action on Sludge Disposal Commission of the European Communities (1975) a stable sludge is one which has received biological or chemical treatment or long term storage. On the other hand, according to US Enviroumental Protection Agency (1995) sludge is to be stabilized in order to siguificantly reduce pathogens or to reduce the volatile solids by a certain percentage. While stabilization in terms of one or a few parameters does not ensure that the sludge is entirely safe to be disposed, no gnarantees as to the nltimate effect of sludge on the enviroument or on human health can be made unless the degree of any treatment is specified.

Nevertheless, in the field of sludge stabilization, anaerobic digestion is by far the most widely selected stabilization process at medium and large sized municipal plant or even in small cities (Metcalf and Eddy, 1991; Verstrate and Vandevivere, 1999; Mata-Alvarez *et al*., 2000; Ahn, 2006). The history

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of anaerobic sludge digestion and its precursors has been traced since 1850 with development of the first tank designed to separate and retain solids. It is interesting to note that the same practice is being followed up-to-date but great progress has been made in the fundamental understanding and control of the process. At the same time, engineers have become aware of limitations affecting anaerobic growing in popularity for use in smaller installation.

The end products of the anaerobic metabolism of organic compounds are methane, unused organics and a relatively small amount of cellular protoplasm. Growth is limited by a lack of hydrogen acceptors. Anaerobic digestion is basically a destructive process according to the following bio-reaction (Tiehm *et al*., 2001):

$$\text{Organic matter} \xrightarrow[\text{Bacteria}]{\text{Anaerobic}} \text{Stable matter} + CO_2 + H_2S + NH_3 + CH_4$$

The process may be divided into three phases: hydrolysis, acidification and methanogenation. The process stability is influenced strongly by the interference of these interims as well as by the physical and chemical structure of organic matter. The extent of anaerobic digestion (conversion into methane) can be expressed using the Specific Methanogenic Activity (SMA) of anaerobic consortium (Sanchez *et al*., 1995; Codina *et al*., 1998; Pierkiel and Lanting, 2005).

The process can either be thermophilic digestion in which sludge is fermented in tanks at a temperature of 55°C or mesophilic, at a temperature of around 36°C. Though allowing shorter retention time, thus smaller tanks, thermophilic digestion is more expensive in terms of energy consumption for heating the sludge. On the other hand, the characteristics of organic matter present in the sludge play an important role in terms of the process stability as a whole. Domestic sludge is categorized as low-strength sludge (Sanchez *et al*., 1995; Dinsdale *et al*., 2000; Houghton *et al*., 2002). Hence, when anaerobic digestion is applied, the microbes remain severely under loaded. The under-loading condition results in a severe lack of substrate for the associated various groups of microorganisms (acidogens, acetogens and methanogens). It is important herewith to overview the real sludge activity to design the process conflguration.

The purpose of the present study was, therefore, to assess the efficiency of the anaerobic process for digestion of low-strength domestic sewage sludge under different thermophilic conditions.

MATERIALS AND METHODS

Experimental Setup

The experimental setup was placed in El-Berka wastewater treatment plant, Egypt. The experimental work was conducted in three batch reactors (Working volume = 1L) under different temperatures (40, 45, 50°C) to ascertain the optimum condition for the degradation process (Fig. 1). Water baths equipped with thermostat were used to control the operating temperature. The experiments were continued until the cease of gas production and the remaining organics was considered as slowly-biodegradable or non-biodegradable fraction.

In addition, all the main reactors were setup in duplicate to validate the experimental results.

Seed Sludge

Each of the three reactors was filled with the same volume of same sludge. Hence, the ouly parameter varied was temperature. The sludge was collected from the sump of the sludge pumping station of El-Berkah WWTP where all the experimental works were conducted. The seed sludge was a mix of primary sludge and waste activated sludge. Table 1 shows the physico-chemical characteristics of the utilized seed sludge.

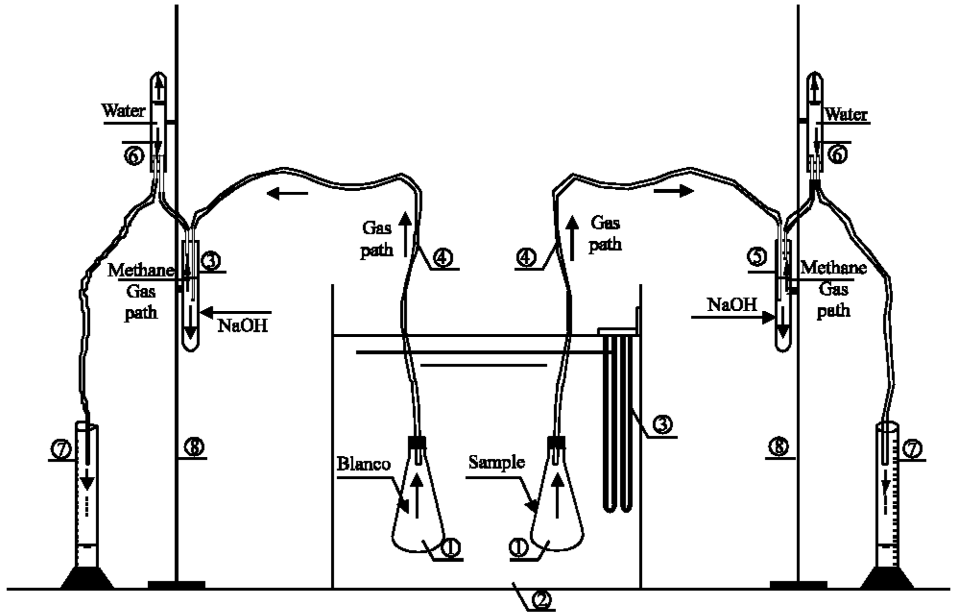

Fig. 1: The experimental setup

Table 1: The physico-chemical characteristics of raw seed sludge

Parameters	Symbol	Unit	Value
Hydrogen ion concentration	pH-value	-	6.1
Total chemical oxygen demand	COD	(mg L^{-1})	5640
Biological oxygen demand	BOD	(mg L^{-1})	1990
Total solids	TS	(mg L^{-1})	22180
Total suspended solids	TSS	(mg L^{-1})	20982
Volatile suspended solids	VSS	(mg L^{-1})	18954
Fixed suspended solids	FSS	(mg L^{-1})	2028
Total dissolved solids	TDS	(mg L^{-1})	1198
Volatile dissolved solids	VDS	(mg L^{-1})	446
Fixed dissolved solids	FDS	(mg L^{-1})	752
Density	δ	(kg L^{-1})	1.30

Sampling and Analysis

A small amount of sample was taken for analysis periodically, i.e., every two or three days from each flask. The stability of the process was assessed in terms of the sludge methanogenic activity as well as all other control parameters that describe the progress of degradation process. Gas production, Chemical Oxygen Demand (COD), Biological Oxygen Demand (BOD_5), different fractions of solids and all physical parameters as shown in Table 1 were monitored. The produced biogas was measured using Marriot flask system (liquid-displacement) as shown in Fig. 1. The gas was flowed through sodium hydroxide solution for moisture absorption before measuring. All analysis were performed according to Standard Methods (APHA, AWWA, WEF, 1998).

RESULTS

The present study focused on the stability of anaerobic digestion of low-strength sludge. The experimental work was conducted under different temperatures within the thermophilic range (40, 45, 50°C) to ascertain the optimum condition for the degradation process. The experiments were run till the cease of gas production.

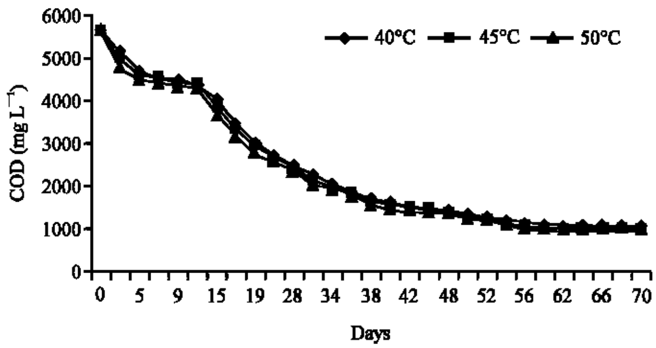

Fig. 2: COD reduction of anaerobic degradation of domestic raw sludge

Table 2: Anaerobic degradation performance at different operating temperatures

	Temperature		
Parameters	40°C	45°C	50°C
BOD reduction (%)	95.90	96.70	97.50
COD reduction (%)	80.70	82.50	83.10
Max pH-value	6.62	6.64	6.64
Min pH-value	6.10	6.10	6.10
TSS reduction (%)	76.00	75.00	74.00
VSS reduction (%)	82.40	83.20	82.90
M-factor	0.25	0.246	0.252

To elucidate the effect of temperature on the reduction of organics content, Fig. 2 shows the COD reduction under different operating temperatures along the entire experimental period. Table 2 shows the performance of the anaerobic degradation process under different temperatures in terms of average reduction of BOD, COD and VSS. The Volatile Suspended Solids (VSS) correspond to the organic matter-content including all biomass in the investigated sludge. Similar removals irrespective of operating temperature were observed. Table 2 also depicts the values of M-Factors under different temperatures. M-Factor indicates the percentage of $COD_{removed}$ that is converted into methane gas; $COD_{converted\ into\ methane}$ (complete digestion). The M-Factor ranged around 0.25 irrespective of the operational temperature.

In this study, the stability of the anaerobic degradation process was also assessed in terms of the methanogenic activity of the biomass present in the investigated sludge. The incremental real methanogenic activity of the investigated sludge under different operating temperature was plotted with time (Fig. 3-5). The incremental methanogenic activity, IMA (gCOD-CH_4/gVSS/day) is the rate of methane gas production (g COD-CH_4) in a time increment (T_i day) from a biomass bulk (VSS_i g), hence:

$$IMA = g\ COD\text{-}CH_4 / [T_i, day \times VSS_i, g]$$

Irrespective of the operating temperature, the maximum methanogenic activity was delayed until the 52nd day. The accumulated methane production rate in terms of COD-CH_4 as well as the accumulated organics removal rate in terms of COD was also plotted in the above-mentioned graphs. Virtually temperature- independent variations were also observed for these parameters.

Table 3 shows the typical removals and methanogenic activities depicted in Fig. 3-5.

Figure 6 shows the level of dissolved organics and inorganics along the experimental period, where the dissolved organics indicate the level of volatile acids (Hydrolysis stability) and the dissolved

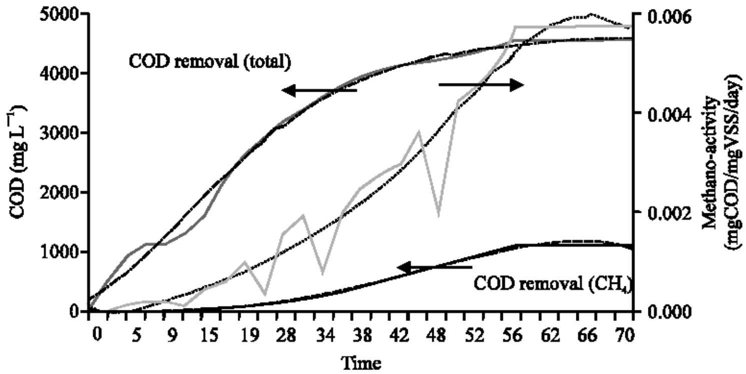

Fig. 3: The performance of anaerobic degradation of domestic raw sludge at 40°C

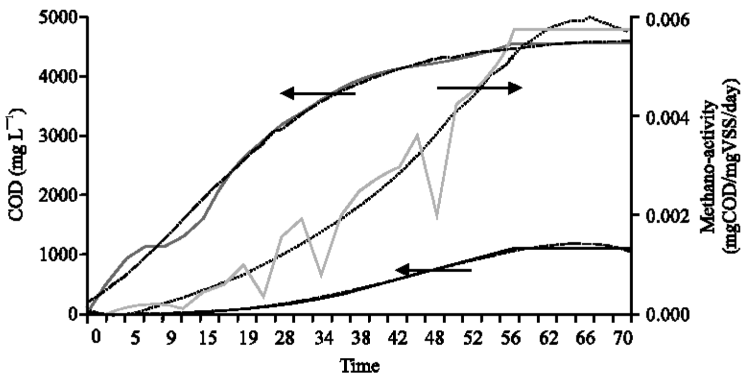

Fig. 4: The performance of anaerobic degradation of domestic raw sludge at 45°C

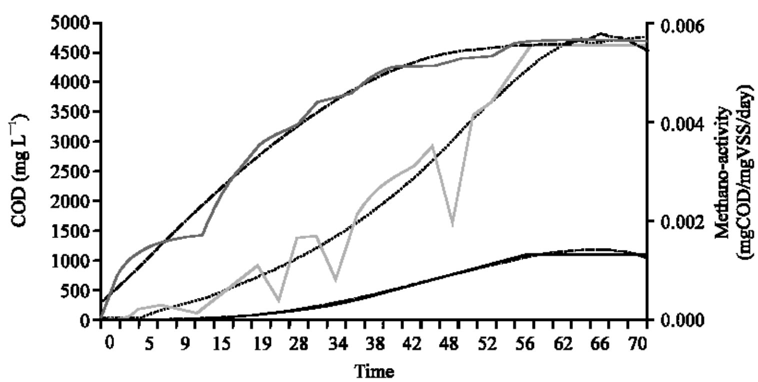

Fig. 5: The performance of anaerobic degradation of domestic raw sludge at 50°C

Table 3: Typical maximum removals and methanogenic activity

Parameters	Value
Total COD removal (%)	81.00
COD removal CH_4 (%)	21.00
Methanogenic activity, gCOD-CH_4/gVSS/day	00.006

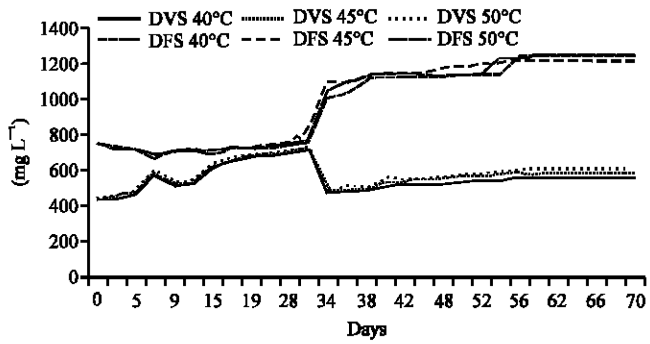

Fig. 6: The level of dissolved organics (DVS) and dissolved inorganics (DFS)

inorganics indicate the level of end products. The level of dissolved organics showed a gradual increase along the first 30 days of the digestion period when the rate of gas production was very slow (Fig. 3, 4, 5). The rate of uptake of these fatty acids, concomitant with increase of gas production, accelerated afterwards. However, the behavior was remarkably independent of the operation temperature.

DISCUSSION

In this study COD reduction followed almost the same trend irrespective of the operating temperature (40-50°C). The observed methanogenic activity as well as M-Factor was also temperature-independent. On the other hand, a long lag time (52 days) preceded the maximum methanogenic activity (Fig. 3-5). The slope of the Cumulative COD removal curve was found to be higher than that of the Cumulative COD-CH_4 curve for the first 34-38 days. During this period the level of volatile acids (indicating hydrolysis stability) also exhibited gradual increase. Nevertheless, with improved methanogenic activity, the uptake- rate of these fatty acids eventually accelerated and onset of increased gas production was observed. Our observation is in line with the available reports on the sensitivity of anaerobic process in case of digestion of sewage sludge (Kevin *et al*., 1991; Rinzema *et al*., 1993; Lin *et al*., 1997; Weemaes *et al*., 2000; Fouad, 2001).

The anaerobic degradation is a high-rate treatment process that relies on the very complicated interrelations among the related microbes. The characteristics of organic matter present in the sludge play an important role in terms of the process stability as a whole. Domestic sludge is categorized as low-strength sludge. Hence, when anaerobic digestion is applied, the microbes remain severely under loaded. The under-loading condition results in a severe lack of substrate for the associated various groups of microorganisms (acidogens, acetogens and methanogens). Lack of substrate is likely to be the reason of requirement of a long lag time to reach the maximum methanogenic activity in this study. Nevertheless, the temperature-independent performance observed in this study was also interesting and may have implications on cost-effective design of anaerobic digestion facilities.

CONCLUSIONS

This study reports the efficiency of the anaerobic process for digestion of low-strength domestic sewage sludge under different thermophilic conditions.

Anaerobic digestion of domestic sewage sludge achieved removals of 81% of COD, 96% of BOD and 74% of TS within about 52 days of inoculation under 40°C. Only a slight increase in removal performance was observed with the increase of operating temperature (45 and 50°C). A small portion of organics was converted to methane and the M-Factor (COD removed into methane/COD removed) ranged around 0.25 irrespective of the operational temperature. The methanogenic activity showed a stable increasing trend after a 34-day lag period during which acidogenic and acetogenic activities were taking place along with continuous COD removal. Irrespective of the operating temperature, the maximum methanogenic activity was delayed till the 52nd day.

The anaerobic degradation process should be designed according to the maximum methanogenic activity (gCOD-CH_4/gVSS/day) and the corresponding required digestion time (days), which, in turn, depend on the composition and characteristics of the sludge.

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