THE USE OF ULTRASOUND TO ACCELERATE THE ANAEROBIC DIGESTION OF SEWAGE SLUDGE

A. Tiehm, K. Nickel and U. Neis

Technical University of Hamburg-Harburg, Gewässerreinigungstechnik, Eißendorfer Str. 42, 21073 Hamburg, Germany

ABSTRACT

The slow degradation rate of sewage sludge in anaerobic digestors is due to the rate limiting step of sludge hydrolysis. The effect of ultrasound pretreatment on sludge degradability was investigated using ultrasound at a frequency of 31 kHz and high acoustic intensities. Ultrasound treatment resulted in raw sludge disintegration as was demonstrated by increase of Chemical Oxygen Demand in the sludge supernatant and size reduction of sludge solids. Semi-continuous fermentation experiments with disintegrated and untreated sludge were done for four months on a half-technical scale. One fermenter was operated as a control with a conventional residence time of 22 days. Four fermenters were operated with disintegrated sludge and residence times of 22, 16, 12, and 8 days, respectively. In the fermenters operated with identical residence times of 22 days reduction of volatile solids was 45.8 % for untreated sludge and 50.3 % for disintegrated sludge. The fermentation of disintegrated sludge was stable even at the shortest residence time of 8 days with biogas production 2.2 times that of the control fermenter. Due to ultrasound disintegration a better degradability of raw sludge was achieved that permitted a substantial increase in throughput.

KEYWORDS

Cavitation; anaerobic degradation; anaerobic digestion; sewage sludge treatment, ultrasound disintegration

INTRODUCTION

Anaerobic fermentation is the most applied process for stabilization of sewage sludge. Mass reduction, methane production, and improved dewatering properties of the fermented sludge are important features of anaerobic digestion. On account of carbon removal in the form of methane and carbon dioxide, the end product shows a substantially better biological stability than the unfermented material. Therefore, disposal on a dumping site or application as a fertilizer are possible. A disadvantage of the fermentation technique is the slow degradation rate of sewage sludge. Conventional residence times in anaerobic digesters are about 20 days, requiring large digesters. Sludge hydrolysis is the rate limiting step of anaerobic digestion (Eastman & Ferguson, 1981; Malina & Pohland, 1992).

The biodegradability of sludge solids can be improved by sludge treatment resulting in solids solubilization. Positive effects were shown for thermal pretreatment (Stuckey & McCarty, 1984; Li & Noike, 1992), addition of enzymes (Knapp & Howell, 1978), ozonation (Yasui & Shibata, 1994), chemical solubilization by acidification (Gaudy et al., 1971; Woodard & Wukasch, 1994) or alkaline hydrolysis (Mukherjee & Levine, 1992), and mechanical sludge disintegration (Müller, 1996). Fullscale application of these engineered solubilization techniques has been limited due to high operating and capital costs.

Using ultrasound for sludge treatment is a new application in the waste water technology. Ultrasound frequences range from 20 kHz to 10 MHz. Particularly at low frequences from 20 kHz to 40 kHz cavitation occurs when the local pressure in the aqueous phase falls below the evaporating pressure resulting in the explosive formation of small bubbles. These bubbles oscillate in the sound field over several oscillation periods, grow by a process termed rectified diffusion, and collapse in a nonlinear manner. Cavitation is accomplished by high pressure gradients, an extreme increase of the temperature inside the bubble, and in the region around the bubble. Therefore, cavitation leads to strong mechanical forces (Atchley & Crum, 1988).

Studies published previously indicate that ultrasound treatment is apt to disintegrate sewage sludge (Kunz & Wagner, 1994; Neis et al., 1994; Müller, 1996; Chiou et al., 1997). These laboratory experiments were done on small scale with a maximum ultrasound reactor power supply of 500 W.

The concept of the fermentation studies is based on the idea that due to cell lysis obtained by ultrasound treatment, the anaerobic digestion is accelerated. Our study was done on a half-technical scale using 150 liter fermenters and a 3,6 kW high performance ultrasound reactor. Experiments focused on the reduction of residence time required in stirred tank fermenters and on the minimization of volatile solids in the digested sludge.

MATERIALS AND METHODS

The fermentation experiments were performed in a pilot plant consisting of five stirred tank fermenters (150 liter) which were operated in parallel at 37 °C. As a control one anaerobic fermenter was operated with untreated raw sludge with a residence time of 22 days. Four fermenters were fed with ultrasonically treated sludge with residence times of 22, 16, 12 and 8 days (fig. 1).

The fermenters were operated semi-continuously. Once a day digested sludge was replaced by appropriate volumes of raw sludge. The raw sludge was obtained as a split flow from a municipal waste water treatment plant with 85.000 population equivalents. The raw sludge of this treatment plant consists of 53 % primary sludge and 47 % excess sludge with respect to the dry solids weight.

Sewage sludge treatment was done with a high performance ultrasound reactor (3,6 kW) especially developed for sludge treatment. This reactor operates at a frequency of 31 kHz. Treatment time in flow-through mode was set to 64 seconds. Due to the ultrasound treatment, temperature of the sludge increased from about 15 ^{o}C to nearly 45 ^{o}C.

The fermentation experiments were performed for four months. Production of biogas was recorded and its composition analyzed by gas chromatography. Volatile solids were determined daily in the influent and in the effluents. The Chemical Oxygen Demand (COD) and the concentration of fatty acids in the effluent supernatants were determined weekly. Supernatants were obtained by centrifugation (30 min at 40.000 rcf) followed by membrane filtration (0,45µm celluloseacetate).

Sludge disintegration was studied using the same ultrasound reactor as in the fermentation experiments. The increase of COD in the sludge supernatants due to ultrasound treatment was determined. For comparison purposes, maximum sludge-disintegration was determined by incubation in 0,5 mol/l sodium hydroxide for 22 hours at 20° C. Particle size distributions were determined by laser light scanning as described previously (Neis & Tiehm, 1996).

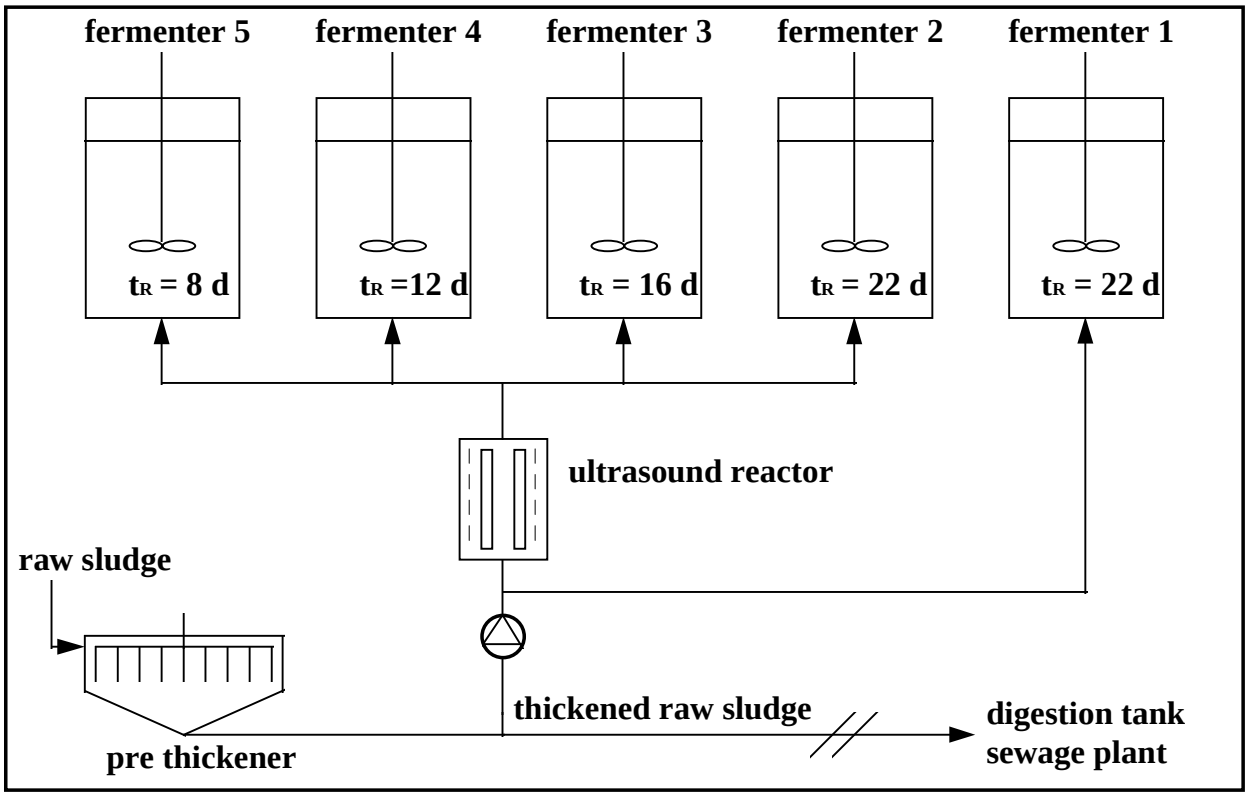

Figure 1. Scheme of the experimental configuration.

RESULTS AND DISCUSSION

Sludge disintegration.

Ultrasound treatment of raw sludge caused a transfer of organic substances from the sludge solids into the aqueous phase as was demonstrated by an increase of COD (fig. 2). After 96 seconds of ultrasound treatment more than 30 % of the maximum disintegration was achieved as compared to the chemical disintegration method.

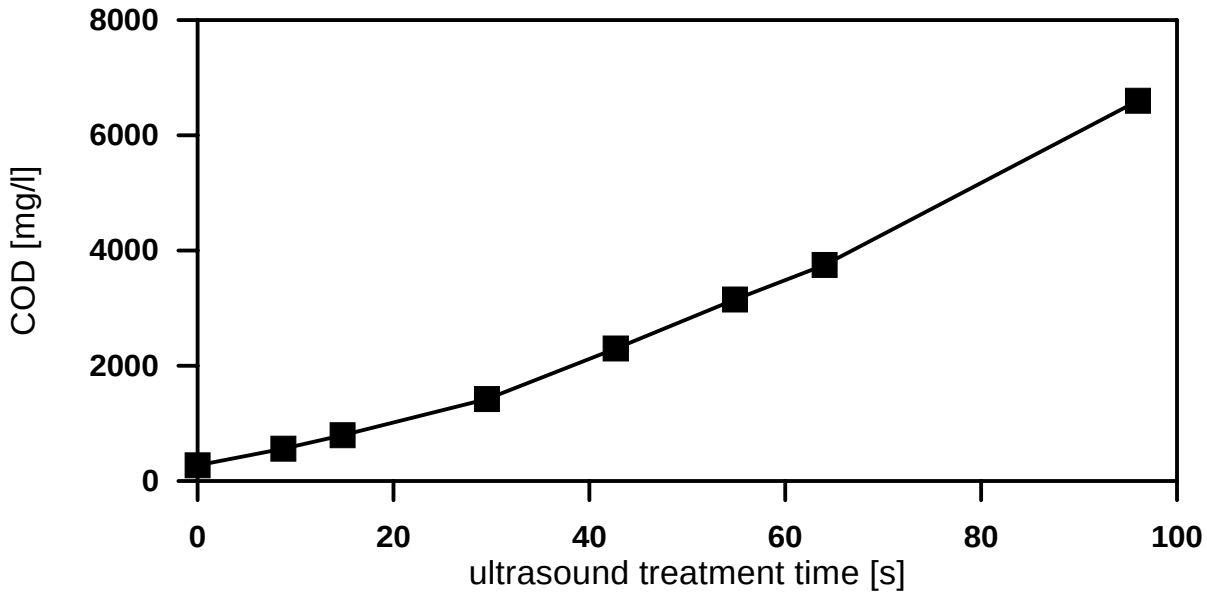

Figure 2. Increase of COD in the sludge supernatant after ultrasound treatment of raw sludge (total volatile solids: 27,8 g/kg).

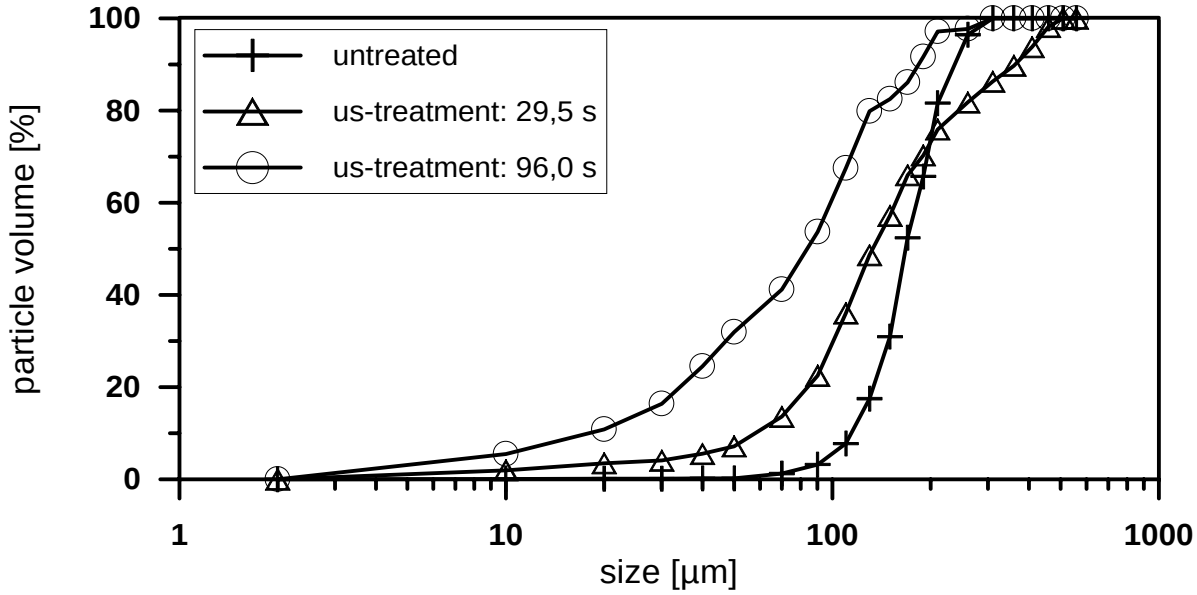

Figure 3. Size reduction of raw sludge solids by ultrasound treatment.

Particle size distributions were determined in the size range from 2 to 600 µm (fig. 3). Corresponding to the release of COD (fig. 2) a significant size reduction of sludge solids was observed: The x_{50}-particle diameter decreased from 165 µm (untreated raw sludge) to 135 µm after 29,5 s and to 85 µm after 96 s of ultrasound treatment.
Size reduction and COD release indicated that the ultrasound reactor generated strong mechanical forces causing aggregate deagglomeration and microbial cell disruption.

Batch fermentation kinetics.

In batch experiments, the degradation kinetics of untreated and ultrasound treated sludge was determined in two 150 l fermenters. Anaerobic sludge from the two digestors with 22 days detention time was taken as inoculum.
An increased rate of biogas production was observed in the reactor receiving disintegrated sludge (fig. 4). Obviously the organic compounds transferred by ultrasound from the sludge solids into the aqueous phase were readily biodegradable.

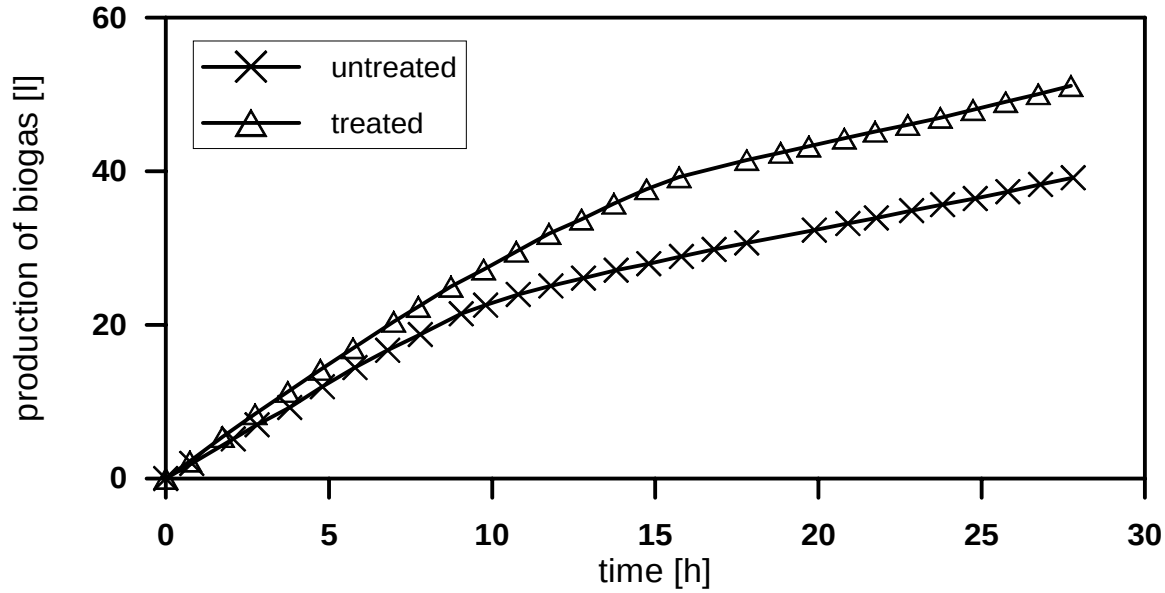

Figure 4. Production of biogas during fermentation of untreated and ultrasound-treated raw sludge (batch experiment).

Semi-continuous fermentation kinetics.

The raw sludge obtained from the municipal waste water treatment plant exhibited large fluctuations during the long-running fermentation study. Volatile solids content ranged from 2.5 g/kg to 38 g/kg. In order to improve clarity of the presentation weekly average values of daily measurements are shown in figure 5. Average volatile solids content in the raw sludge decreased from 24 g/kg to 14 g/kg within the first two months of the semi-continuous fermentation. Afterwards average volatile solids content increased again to a concentration of 28 g/kg (fig. 5a). It is obvious that time courses of volatile solids in the fermenter effluents followed the fluctuations of the influent (fig. 5b and 5c). Ultrasound treatment of the raw sludge resulted in an average increase of soluble COD from 630 mg/l in the untreated sludge to 2270 mg/l after ultrasound desintegration.
Figure 5b presents the volatile solids in the effluents of the two digesters operated with a residence time of 22 days. One digester was operated with ultrasound treated raw sludge, the other with untreated raw sludge. Remarkably volatile solids in the effluent of the digester fed with disintegrated sludge was 10 % less than in the conventional process. In the fermenters operated with disintegrated raw sludge the volatile solids in the effluent were not increased even at reduced detention times down to 8 days (fig. 5c). Fluctuations were mostly pronounced in the fermenter with the highest throughput due to the changes in the influent.

The degree of raw sludge degradation was calculated with respect to volatile solids (table 1). The varying concentrations of volatile solids in the raw sludge input and the effluent output have been taken into consideration.

Table 1. Effect of ultrasound treatment and digestion time on sludge degradation.

raw sludge	residence time [d]	reduction of volatile solids [%]
untreated	22	45,8
disintegrated	22	50,3
disintegrated	16	49,3
disintegrated	12	47,3
disintegrated	8	44,3

Anaerobic digestion was significantly improved by ultrasound pretreatment of the raw sludge. Ultrasound disintegration enhanced the degradation even at a reduced residence time of 12 days. At the shortest detention time under investigation the reduction of volatile solids decreased slightly to 44,3 % as compared to 45,8 % obtained with the conventional anaerobic digestion with a residence time of 22 days (table 1).

Significantly higher amounts of biogas were produced in the fermenters fed with disintegrated sludge and operated at reduced residence times. The enhanced conversion of raw sludge into biogas corresponds to the enhanced throughput-rates (fig. 6). Despite the more pronounced reduction of volatile solids in the fermenter operated with disintegrated sludge at a residence time of 22 days there is no increased production of biogas as compared to the control fermenter operated with untreated sludge (table 1, fig. 5b). This may be due to changes in the biochemical fermentation process. Further investigations are required to enlighten anaerobic biodegradation under these conditions.

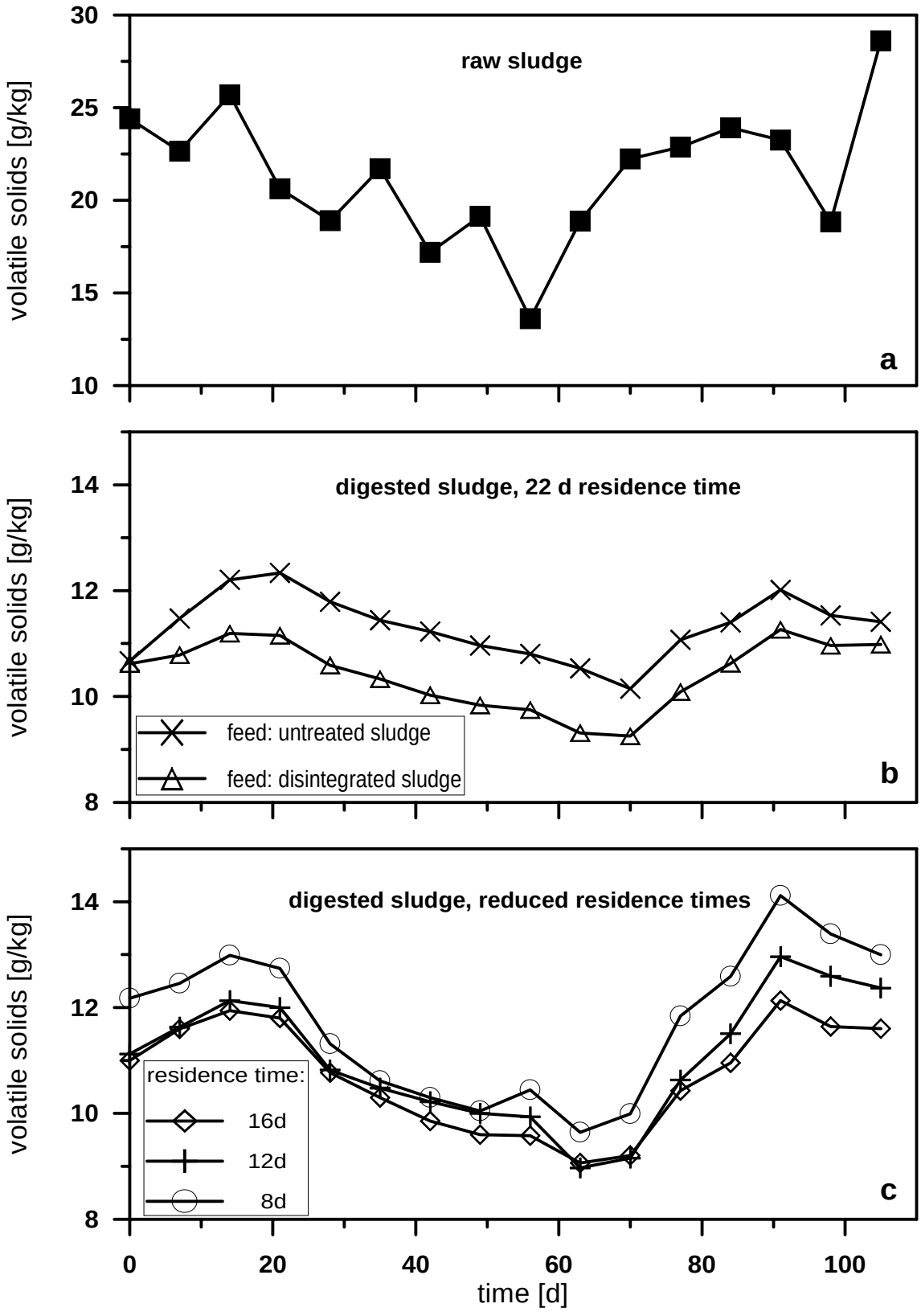

Figure 5a-c. Volatile solids in (a) the raw sludge, (b) the effluents of two digesters operated at a residence time of 22 days, and (c) the effluents of the digesters operated with disintegrated raw sludge at reduced residence times.

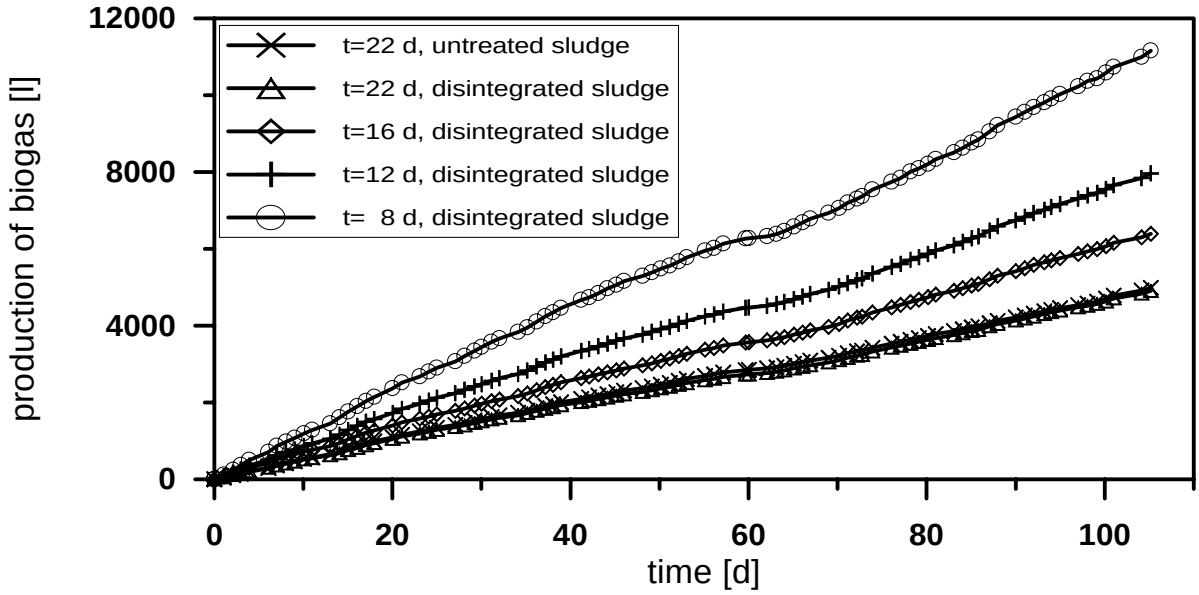

Figure 6. Increase of biogas production at reduced residence times during the fermentation of disintegrated raw sludge (semi-continuous fermentation).

The biogas consisted in all fermenters of 2/3 CH_4 and 1/3 CO_2. This composition remained constant during the four months of fermentation. The concentration of the fatty acids acetate, propionate, butyrate, valerate and capronate was below 100 mg/l in all cases.

It is obvious that in this study the fermentation processes were stable even at very reduced detention times. Stuckey & McCarty (1984) reported that sludge biodegradability was reduced after thermal sludge pretreatment at temperatures above 200 ^{o}C. Such inhibitory effects were not observed after sludge pretreatment with ultrasound despite the high temperatures that have to be expected within the cavitation bubbles (Atchley & Crum, 1988).

CONCLUSIONS

Our experiments clearly demonstrate that ultrasound treatment is a suitable method to disintegrate sewage sludge. Due to sludge disintegration, organic compounds were transferred from the sludge solids into the aqueous phase resulting in an enhanced biodegradability.
In semi-continuously operated fermenters with identical residence times of 22 days reduction of volatile solids was 45.8 % for untreated sludge and 50.3 % for disintegrated sludge. Reduction of volatile solids was 44.3 % in the fermenter operated with disintegrated sludge and 8 days residence time. In this fermenter the production of biogas was significantly enhanced due to the increased throughput. According to the concentration of fatty acids, the biogas poduction, and the biogas composition the anaerobic systems receiving ultrasound treated raw sludge were stable even at reduced digestion times. Therefore ultrasound pretreatment of sewage sludge is a promising method to enhance fermentation rates and to reduce the volume of sludge digesters.

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