The influence of temperature and SRT on high-solid digestion of municipal sewage sludge

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ABSTRACT

The influence of temperature and SRT on high-solid digestion of municipal sewage sludge was investigated in laboratory scale reactors. Digestion with high-solid concentration reduces the required digestion volume and is advantageous for urban areas. The experimental conditions comprised TSS in digested sludge between 4.0 and 4.6 %, temperatures in a range of 33 to 41 °C and the SRT between 10 and 25 d. High-solid digestion operates with increased NH_4-N concentrations released from organic compounds. The anaerobic process can be limited by high NH_4-N concentration and toxic NH_3. In this study a stable digestion was observed up to 2,000 mg L^{-1} NH_4-N and 75 mg L^{-1} NH_3. VSS and COD removal was 53 % respectively 57 %. However, digestion with 10 d SRT led to a declined VSS removal of 49 %. The removal at 41 and 37 °C showed minor differences, while reduced NH_4-N release and methane production were observed at 33 °C. For economic reasons, high-solid digestion at 41 °C is not recommended, but will not impair VSS removal. The outcomes of this study confirm that digestion with up to 7.8 % TSS in the feed is feasible for the tested temperatures and SRT down to 15 d.

INTRODUCTION

Anaerobic digestion is one of the major technologies for the stabilization of sewage sludge of wastewater treatment plants (WWTPs). With a trend to more energy efficient wastewater treatment and the desire to reduce GHG emissions, there is a strong development towards anaerobic digestion for sewage sludge worldwide. Hereby the disposal and energy costs are minimized by converting organic compounds into energy-rich methane gas and as a result stabilize the sludge. Typically, wastewater treatment defines SRT as solids retention time. The required digestion volume results from the raw sludge volume and SRT. Sludge thickening before digestion is used to remove water and to ensure smaller sludge streams. As a result, a reduced digestion volume and physical footprint are possible. Another benefit of thickening can be seen in a reduced energy demand for sludge heating, as less water is required to be heated.

High-solid digestion is characterized by 3 to 4 % TSS in the digested sludge, which results from an increased solid content in the feed. There is limited information in literature about optimum operating conditions for high-solid digester that can be used to inform the design. Most reports of high-solid digestion relate to the treatment of municipal organic waste streams (Kayhanian 1994; Guendouz *et al.* 2008; Le Hyaric *et al.* 2011), whereas only few studies exist for the high-solid digestion of municipal sewage sludge (Kapp 1984; Lay *et al.* 1997; Fujishima *et al.* 2000; Duan *et al.* 2012). Because of the lack of information and for safety reasons, the digesters of WWTP are often operated only with solid contents in a range of 2 to 3 %. Compared to well described studies about the digestion with lower TSS, this study focus only on experiments with TSS in the digested sludge of about 4 %.

High-solid digestion shows a number of advantages especially for the economical sludge treatment in urban areas. Besides an increased polymer demand for sludge thickening, it is attractive for WWTPs that have a need to increase capacity and are constrained by space. However, high-solid sludge has different rheological flow characteristics compared to low solid sludge. For this reason, the digester design requires adjusted hydraulic pipe design. Moreover, the high-solid content in the digested sludge leads to increased NH_4N concentrations in the dewatered effluent. The returned nutrient load can be treated separate in tanks or combined in the biological stage. No matter how, the treatment of turbid water lead to enhanced aeration and energy demand. To reach an economic operation of high-solid digestion, other costs must be kept low, especially increased disposal costs caused by a potentially decreased sludge degradation. While a reduced methane production impairs the energy recovery, a decreased removal can cause a declined dewaterability of digested sludge and increased polymer demand or disposal costs. The influence of individual factors on the degradability are described below.

An important parameter for the anaerobic treatment is the SRT (eq. hydraulic retention time). HRT is the time the water is in the digester, so it is not necessarily equivalent to SRT. It is known, that with longer SRT a wider range of substrates, especially slowly degradable carbohydrates can be hydrolyzed to easy available compounds resulting in high removal efficiency (Young *et al.* 2013). Kapp (1984) reported an increased VSS removal of high-solid sludge at 30 d SRT compared to 15 d. The German design recommendations for digesters name a minimum SRT of 15 d (DWA 2014). However, most digesters on WWTPs are operated with SRTs of 25 d. SRT needs to be reduced in the cases of treating additional organic waste streams (co-digestion), demographic increase or disturbances (decommissioning digester). Some authors report that a sufficient removal is possible also with 10 d SRT (Nges & Liu 2010; Lee *et al.* 2011). Nevertheless, short SRT can decrease VSS removal and dewaterability. This in turn increase sludge disposal costs and shows the importance of a sufficient degradation (Skinner *et al.* 2015).

Another relevant operation parameter is the temperature. Mostly, mesophilic temperatures are applied; although thermophilic digestion processes reach a higher reduction of organic compounds, it is known to be more cost intensive. Additionally, thermophilic bacteria prefer a narrow temperature range, which makes the process unsuitable for temperature shifts. International textbooks name design temperatures for mesophilic fermenters in a range of 30 to 38 °C (Metcalf & Eddy 2004). For the mesophilic operation it is reported that the microbial community adapt on their environment when temperature was changed slowly. However, until now it is not clear which effect temperature shifts will have for a digestion with high-solids, when more ammonium (NH_4-N) is released compared to digestion with low solid concentrations.

While operational settings like temperature or SRT result mainly from the design basis, the NH_4-N release relates mainly to the breakdown of protein containing compounds and is adjustable only by controlling the solid concentration of the feed. Hence, NH_4-N in digested sludge correlates with the amount of supplied raw sludge and its solid concentration. It is known that high NH_4-N concentration can inhibit especially methanogenic bacteria (Hansen *et al.* 1998; Sung & Liu 2003; Rajagopal *et al.* 2013; Yenigün & Demirel 2013). Wiegant and Zeeman (1986) as well as Angelidaki and Ahring (1993) found that acetoclastic methanogenic are more resistant to high ammonia concentration, while hydrogenotrophic methanogenic bacteria do not or only slowly adapt on increased concentration. Hydrogenotrophic methanogenic bacteria are essential to keep hydrogen concentration low and thus to enable the conversion of propionic into acetic acid and hydrogen (Fujishima *et al.* 2000). A negative impact on the digestion of sewage sludge was reported above 2,000 mg L^{-1} NH_4-N (Duan *et al.* 2012; Hidaka *et al.* 2013). At the same time increased temperatures and pH strengthen the inhibitory effect by forming toxic ammonia (NH_3). Hence, the inhibition of high-solid digestion by NH_3 is a result of the combination of NH_4-N concentration, temperature and pH. Lay *et al.* (1997) investigated the influence of moisture content and pH on the methane production in high-solid fermentation. The authors observed at moisture contents of 90 to 96 % a pH range between 6.6 and 7.8. Optimally results appeared at pH 6.8.

Due to the known negative influence of high NH_4-N concentration to anaerobic bacteria, it has to be considered to what extent NH_4-N concentration result from the digestion of a high-solid feed and whether there is an impact on biodegradation or methane production. Particular attention was therefore paid to released NH_4-N and NH_3. In this study the influence of temperatures in a range of 33 to 41 °C and SRT of 10 to 25 d on high-solid digestion were investigated to characterize the process stability in view of a large scale treatment. The investigated temperatures cover the often named optimum of 37 °C for mesophilic operation and temperatures with a trend to psychrophilic and thermophilic conditions. SRT was selected to compare the performance of values usually applied for digesters on WWTPs with shorter SRT to find the optimal operation. Moreover, the removal of volatile suspended solids (VSS) and chemical oxygen demand (COD) as well as the specific methane production according to the tested conditions were evaluated. The aim of this study was to test different stress conditions and to describe the expected impacts on the anaerobic conversion with higher solid content. Acid concentrations were therefore used as tool to evaluate process stability.

MATERIAL AND METHODS

The experimental set-up consisted of three identical reactors with a volume of 3.0 liters. The reactors were inoculated with digested sludge from a municipal WWTP, digesting sewage sludge at low solid concentration under mesophilic conditions. All reactors were fed semi-continuously, once per day on five days per week with raw sludge. The raw sludge was taken from a static thickener of a WWTP. There, excess and primary sludge were thickened at once, while excess sludge is often thickened separate with mechanical techniques.

A heated water bath was used to control different temperatures. Temperature and pH were controlled every day by using a WTW SenTix20 pH meter. The dosage of chemicals to set optimal pH was not necessary. A stirring system ensured continuous sludge mixing. The reactors were directly attached to drum gas meter to measure the gas flow (Ritter, type

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Bochum Langendreer 11066). Gas was analyzed by a GFM 400 gas analyzer to determine the methane content. Sludge samples were mainly analyzed for COD, total suspended solids (TSS), VSS, total kjeldahl nitrogen (TKN) and by standard methods (NH_4-N and orthophosphate). Organic acids were measured by an isocratic high performance liquid chromatographic (HPIEC) method including the separation and quantitative analysis of organic acids. Organic acids were summarized as concentrations of formic, butyric, valeric, acetic, propionic and lactic acids.

The experiments were divided into five periods. Table 1 summarizes the applied temperatures and SRTs. After changing temperature or SRT, the reactors were allowed to stabilize for more than one SRT before the evaluations were made for the individual periods. For each phase the organic loading rate (OLR) and SRT were identical for all reactors. Raw sludge and digested sludge samples were analyzed twice a week. The data were used to calculate the COD and VSS removal, specific methane production and nitrogen release. The measurements of every period were controlled by mass balances for COD and total phosphorus (TP). Analytical data of the raw sludge were compared to identify annual fluctuations in sludge quality. The ratio of primary and excess sludge defines the biodegradability and gas production. Hence, slight variations in the degradability of raw sewage sludge over longer periods are usual due to variations in the sludge composition.

The TSS of the feed sludge varied between 6.7-7.8 %. Sludge samples were moreover compared in terms of the nitrogen load; especially TKN and NH_4-N. In the first experiments in raw sludge, mean NH_4-N concentrations of about 700 mg L^{-1} were observed, while in the following periods the mean NH_4-N concentrations were lower with 250 to 550 mg L^{-1}. Moreover; a high ratio of TKN to VSS of about 7.3 was determined during the first period. The ratio of TKN to VSS decreased during period 2 to 5 and was then found between 5.8 and 6.7. The differences can be explained by increased environmental temperatures during period 1, which took place in the summer period of June to August. Static thickening of raw sludge with high environmental temperatures or longer storage time can favour the hydrolysis of proteinaceous compounds and subsequently the total removal. Additionally; the proportion of VSS and TSS of raw sludge was calculated. During the first experiments the ratio was about 1.96. A further hydrolysis of organic compounds caused by higher temperature is hereby combined with decreasing VSS concentrations, which finally leads to a high ratio of TSS/VSS. In the following months the temperatures were colder, resulting in a slight decreased ratio of TSS/VSS to finally 1.71.

Table 1: Operation adjustments and mean analytical data of used raw sludge

Item		Unit	period 1	period 2	period 3	period 4	period 5
adjustment	n*	[-]	10	5	7	9	6
	$t_{R1,R2,R3}$	[°C]	39;37;35	41;37;33	41;37;33	41;37;33	41;37;33
	SRT	[d]	25	25	20	15	10
mean sludge composition	TSS	[%]	6.7±1.1	6.8±0.2	7.0±0.4	7.1±0.5	7.6±0.6
	TSS/VSS	[-]	1.96±0.1	1.81±0.1	1.75±0.1	1.74±0.1	1.71±0.1
	COD/VSS	[-]	1.34±0.0	1.27±0.0	1.25±0.0	1.22±0.0	1.25±0.1
	TKN/VSS	[%]	7.32±0.5	6.68±0.4	5.78±2.4	5.75±2.0	6.52±0.5
	org. N	[g L^{-1}]	3.20±0.8	2.99±0.2	3.49±0.4	3.30±0.3	3.59±0.2
	NH_4-N	[mg L^{-1}]	716±388	550±240	245±134	365±180	365±170

* number of measurements

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RESULTS AND DISCUSSION

1. NH_4-N concentration

An essential point of evaluation concerns the production of NH_4-N within the digested sludge. Figure 1 depicts the NH_4-N concentration of raw sludge and digested sludge samples. NH_4-N concentrations peaked up to 2,000 mg L^{-1} especially during the first phase. This was mainly caused by increased NH_4-N concentration in the feed. A reason for this is the increased hydrolysis during thickening due to increased temperatures during the months June to August. In the following two periods, NH_4-N in digested sludge stabilised at 1,600 and 1,860 mg L^{-1} due to lower concentrations in the feed. However, the TKN load remained almost the same, which represented a constant total nitrogen load. Moreover, the lowest concentrations in the input were found during period 3 due to low temperatures of the months November and December. The findings of this study demonstrate that the NH_4-N concentrations were mainly affected by the degree of hydrolysis and not by TSS concentration, since the TSS in digested sludge was almost stable around 40 g L^{-1} (38.0 to 46.0 g L^{-1}). However, this observation refers to TSS in the feed of 6.7-7.8 %. Thus, NH_4-N concertation of 2,000 mg L^{-1} can naturally occur by treating sewage sludge with higher TSS and an increased hydrolysis during pre-treatment.

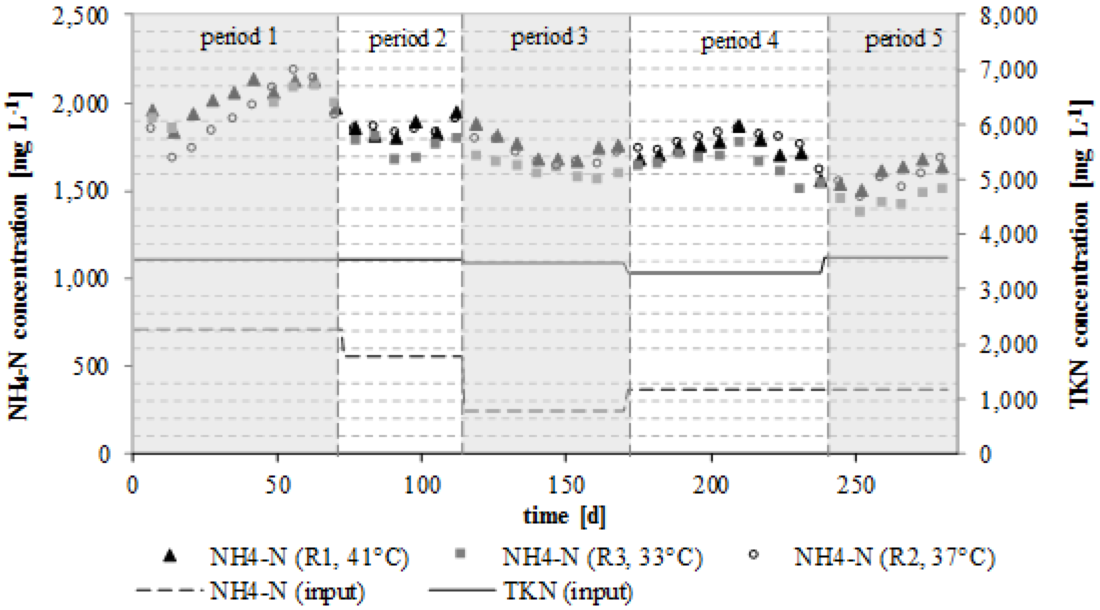

Figure 1: Mean NH_4-N and TKN concentration of raw sludge and NH_4-N concentration of digested sludge samples

2. NH_3 concentration

Table 2 summarizes the main conditions resulting for the applied temperatures and SRTs in the three reactors as average values. NH_3 was calculated based on equations from Hobiger (1996). Taking into account that NH_3 formation relates to temperatures; the highest concentrations occurred still at 41 °C. However, NH_3 was all time below than 75 mg L^{-1}. Duan *et al.* (2012) reported a moderate inhibition at mesophilic temperatures by free ammonia concentrations of 400 mg L^{-1}. Sung and Liu (2003) found a reduced methane production of 39 % and 64 % by total ammonia concentrations of 4,920 and 5,077 mg L^{-1}. The comparison of NH_4-N and NH_3 to references from literature indicates that there were no critical values during the experiments which would cause inhibition of organisms. It has to be mentioned, that the results relate to the digestion of sewage sludge with TSS of about 7.8 %. Nevertheless, NH_4-N has to be considered in view of applying co-digestion. Generally, co-digestion is therefore suitable for substrates which have very low or no nitrogen due to the resulting impact on the water stream of a WWTP.

Table 2: Mean analytical parameters of the reactors at temperatures of 33 to 41 °C and 10 to 25 d SRT

SRT	reactor (temperature)	Ø TSS [g L^{-1}]	Ø NH_4-N [mg L^{-1}]	Ø NH_3 [mg L^{-1}]
25 d	R1 (39 °C)	40.7±2.68	2,023±101	69.3
	R2 (37 °C)	41.0±2.13	1,903±43	57.1
	R3 (35 °C)	39.9±3.66	1,933±156	47.3
25 d	R1 (41 °C)	38.3±4.37	1,859±58	75.3
	R2 (37 °C)	37.7±4.28	1,760±64	51.1
	R3 (33 °C)	38.4±4.27	1,851±43	33.6
20 d	R1 (41 °C)	41.1±1.15	1,752±79	72.5
	R2 (37 °C)	40.8±1.24	1,627±56	48.6
	R3 (33 °C)	40.5±1.85	1,701±71	31.0
15 d	R1 (41 °C)	40.1±1.20	1,742±95	75.3
	R2 (37 °C)	39.5±1.35	1,653±100	50.3
	R3 (33 °C)	39.5±1.59	1,781±74	33.0
10 d	R1 (41 °C)	46.0±2.18	1,578±83	55.9
	R2 (37 °C)	44.0±2.66	1,437±58	35.7
	R3 (33 °C)	46.0±2.20	1,547±81	23.4

3. Nitrogen concentration

An overall lower removal can also occur when an incomplete hydrolysis of poorly degradable substances appears. Especially cellulose as carbohydrate-rich compounds is difficult to break down, while proteins are more available for organisms (Young *et al.* 2013). Hydrolysis is a process of the first order and independent from the anaerobic or aerobic conditions. It is known that SRT and temperature influence hydrolysis. (Miron *et al.* 2000; Ferreiro & Soto 2003). To consider the breakdown of organic compounds, NH_4-N release was calculated in relation to the removed COD. This relation could be applied to identify the more reduced organic groups and the progress of hydrolysis. Hydrolysis is often found to be the rate limiting step of particulate substances in the anaerobic conversion and therefore important for the process efficiency (Miron *et al.* 2000; Ferreiro & Soto 2003; Mahmoud *et al.* 2004). Table 3 shows the NH_4-N release, calculated as percentage from the total supplied organic nitrogen load and the ratio of released NH_4-N to degraded COD at the tested conditions. Hereby, the calculated ratio of released NH_4-N to degraded COD at 15 to 25 d SRT occurred in a narrow range. A clear increased ratio was observed with 10 d SRT, while more nitrogen compounds were released than carbon removed representing a reduced hydrolysis of carbon compounds.

For the evaluation of the breakdown; the NH_4-N release was further expressed as ratio to the total supplied organic nitrogen load. As mentioned before, the nitrogen released during the first experiments was slightly enhanced because of higher environmental temperatures and subsequently stronger hydrolysis during static thickening. The NH_4-N released for temperatures of 37 and 41 °C with 15 to 25 d SRT fluctuated only slightly and reached about 42 (±2) %. Beside low differences between 37 and 41 °C; the lowest NH_4-N release was always found at 33°C with 39 (±2) %. The observation clarifies the correlation between temperatures and hydrolysis as reported by Ferreiro and Soto (2003). A lower release of NH_4-N for all temperatures was even determined in the tests with 10 d SRT, that was mainly caused by and insufficient degradation of organic load by short retention time.

Table 3: NH_4-N release of the reactors at temperatures of 33 to 41 °C and SRTs of 10 to 25 d

SRT	reactor (temperature)	Ø ΔNH_4-N/ΔCOD [mg g^{-1}]	Ø NH_4-N release [%]
25 d	R1 (41 °C)	24.6	43.8
	R2 (37 °C)	24.8	44.4
	R3 (33 °C)	23.1	40.4
20 d	R1 (41 °C)	27.7	43.6
	R2 (37 °C)	27.3	42.4
	R3 (33 °C)	26.5	40.0
15 d	R1 (41 °C)	23.6	40.7
	R2 (37 °C)	24.0	42.6
	R3 (33 °C)	22.0	38.5
10 d	R1 (41 °C)	37.5	35.5
	R2 (37 °C)	37.1	33.6
	R3 (33 °C)	33.0	30.5

4. Removal performance and gas production

Table 4 summarizes the results of degradation for the different operating conditions. VSS and COD removal were calculated from the total initial load, the total effluent load and changed amount in digested sludge over the operation period. The first period with 25 d SRT showed an increased removal compared to the following experiments. As mentioned before, an intensified hydrolysis during the thickening and subsequently a higher degradation was expected. After the first period, the experiments were interrupted and the reactors refilled with fresh sludge. In this context, an overall reduced VSS removal of 49 % was observed with likewise 25 d SRT. It can be assumed, that the differences result from an insufficient start-up period and incomplete adaptation of biomass to the increased temperatures and TSS. The importance of a sufficient acclimation of bacteria to higher ammonia nitrogen concentration was also reported by Fujishima *et al.* (2000). The results of these investigations with 25 d SRT were therefore not considered in detail. Similar results as in period 1 were found with a SRT of 20 and 15 d. The removal here was about 53 % (VSS) and 57 % (COD). A stable operation was reached with 15 to 25 d SRT and OLR in a range of 2.0 to 3.8 g VSS m^{-3} d^{-1}.

A declined removal was seen by reducing SRT to at least 10 d, while COD and VSS removal was about 7 % (absolute) lower compared to the test with 15 d SRT. A lower removal efficiency was also seen in an increased TSS in digested sludge of about 44 to 46 g L^{-1}. Moreover, organic acid concentrations during the experiments with 10 d SRT appeared up to

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810 mg L^{-1}. Similar observations were reported by Kapp (1984), who found a VSS reduction of 50 to 54 % at TSS of 4.5 % and SRT of 15 to 30 d, while enhanced TSS of about 7 % in digested sludge leads to a reduced VSS removal of 45 to 48 %. A clear influence of SRT and OLR on VSS reduction was also recognized by Duan *et al.* (2012). In this study, the increase of OLR and the reduction of SRT, lead to increasingly acid concentration. The accumulation can be explained by a delayed degradation of acids formed during acidogenic phase. Since the conversion rate of acidogenic microorganisms are higher compared to the conversion rate of methane forming microorganisms, more acids are produced than consumed when the load exceeds an upper limit. During the experiment with 10 d SRT, OLR was about 5.5 g VSS m^{-3} d^{-1}. For the reason of acid accumulation, the alkalinity in digested sludge is important, while a low alkalinity is known to induce the appearance of not dissociated acids which inhibit bacteria. Normally sewage sludge has a high alkalinity that buffers pH shifts. In this study, pH dropped by changing SRT from 15 d to 10 d SRT from about 7.35 to 7.25 and was despite the increased acid concentration in an optimal range.

Comparing the VSS and COD removal at the investigated temperatures; there were only minor differences. As a result of this study a low degradation, such as that observed here when applying a 10 d SRT, can cause decreased dewaterability with higher polymer demand and disposal costs. This hypothesis is supported by findings from Miron et al. (2000), who found a clearly decreased dewaterability of digested sludge by reducing SRT from 15 to 10 d. Furthermore, a reduced dewaterability by changing SRT from 30 d to 8 d was observed by Kapp (1984). The optimal results of dewaterability for mesophilic temperatures were reported by Mahmoud et al. (2006) with SRT in a range on 15 to 20 d.

Table 4Additionally, the methane production was calculated in relation to the supplied VSS. Methane production is important for the energy recovery by WWTPs. Methane production of about 380 NmL g VSS_{IN}^{-1} were observed in the first experiments, which correlate to an increased removal and were mainly caused by higher environmental temperature. The methane yields at the following tests with 25 to 15 d SRT were much lower, while the highest amounts of 350 to 360 NmL g VSS_{IN}^{-1} were determined at 37 °C. A 2.9 to 10.1 % lower methane production was observed at 33 °C, while the methane yield at 41 °C was only 1.5 to 4.8 % lower compared to 37 °C. This result corresponds with research from Bouskova *et al.* (2005), while in the situation of changing the temperature from 37 to 42 °C only minor changes in gas production were seen. However, for economically reasons temperatures of 41 °C should not be applied at large-scale.

Moreover, the investigated methane production for 15 to 25 d confirm findings from Nges and Liu (2010); they observed 0.314 to 0.348 °Nm^3 CH_4 kg VSS_{IN}^{-1} at SRT between 12 and 35 d; while an unstable process was found at 9 d SRT. For this study a decreased methane production was found for all tested temperatures at 10 d SRT; while the conversion with 41 °C was not that strong influenced like it was observed for 33 and 37 °C. This outcome is similar to findings from Nges and Liu (2010). They found that under thermophilic conditions the VSS removal showed better performance at shorter SRTs (15-5 d); while mesophilic digestion reached higher VSS removal at longer SRT (35-20 d). It can be assumed that higher temperatures at short SRT improve the breakdown of biopolymers and are responsible for the comparatively higher methane production and removal.

An important sludge property that was not investigated in this study, but is significant for WWTP, is the dewaterability of digested sludge. Skinner *et al.* (2015) described the link between VSS concentration and dewatering behavior by comparing fifteen sludges with VSS concentration of 40 to 80 %. As a result of this study a low degradation, such as that observed here when applying a 10 d SRT, can cause decreased dewaterability with higher polymer demand and disposal costs. This hypothesis is supported by findings from Miron *et al.* (2000), who found a clearly decreased dewaterability of digested sludge by reducing SRT from 15 to 10 d. Furthermore, a reduced dewaterability by changing SRT from 30 d to 8 d was observed by Kapp (1984). The optimal results of dewaterability for mesophilic temperatures were reported by Mahmoud *et al.* (2006) with SRT in a range on 15 to 20 d.

Table 4: Mean organic acid concentrations, VSS and COD removal and specific methane yield at temperatures of 33 to 41 °C and SRT of 10 to 25 d

SRT	reactor (temperature)	VSS removal [%]	COD removal [%]	spec. CH_4 prod. [mL $gVSS_{IN}^{-1}$]	Ø acids [mg L^{-1}]
25 d	R1 (39 °C)	50.6	60.7	381	59.8±30
	R2 (37 °C)	53.0	62.7	387	69.1±73
	R3 (35 °C)	-	-	-	54.8±35
25 d*	R1 (41 °C)	48.0	56.0	333	40.1±214
	R2 (37 °C)	49.8	58.2	367	22.0±12
	R3 (33 °C)	48.6	57.4	330	25.4±12
20 d	R1 (41 °C)	52.4	57.2	339	54.4±589
	R2 (37 °C)	55.9	59.3	356	29.3±21
	R3 (33 °C)	53.1	57.7	327	24.4±24
15 d	R1 (41 °C)	53.4	57.5	341	40.8±143
	R2 (37 °C)	53.8	57.7	346	42.6±28
	R3 (33 °C)	54.3	57.3	336	54.5±36
10 d	R1 (41 °C)	47.5	53.0	330	74.5±64
	R2 (37 °C)	46.1	49.9	286	810.0±523
	R3 (33 °C)	47.8	49.9	320	551.0±678

* not considered in detail, because of an insufficient start-up period and incomplete adaptation of biomass

Conclusion

The results of this study indicate that digesters of municipal WWTPs can be operated at high-solid concentrations as long as a minimal sludge age of 15 d is ensured and NH_4-N remains below 2,000 mg L^{-1}. The findings refer to high-solid digestion of raw sludge with TSS in a range of 6.7 to 7.8 %. High-solid digestion with 10 d SRT results in an unstable process and reduced breakdown of carbonate-rich compounds. The right selection of the operational temperature is important for a cost-effective anaerobic treatment. Temperatures of 41 °C did not improve the reduction or the gas production nor did it lead to an unstable process by forming NH_3. However, the higher energy demand for sludge heating makes a large scale operation with 41°C unattractive. It was observed that temperatures of 33 °C led to a reduced breakdown of COD compounds and decreased methane production. Thus, temperatures of 33 °C should not be applied to reach an efficient energy recovery. The impact of solids in the feed above 8.0 % and subsequently the resulting NH_4-N concentration should be examined separately. Furthermore, an advanced investigation of sludge dewaterability can be helpful to calculate total cost effectiveness of different treatment options.

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Abbreviations

COD	chemical oxygen demand
SRT	sludge retention time
OLR	organic loading rate
TSS	total suspended solids
VSS	volatile suspended solids
WWTP	wastewater treatment plant

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