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Variation of the digester temperature in the annual cycle – using the digester as heat storage

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Abstract

Regarding digesters, present guidelines assume that the temperature must be kept constant in order to achieve process stability and that there is a drop in gas production between 40 and 50 °C. Nevertheless, observations of full-scale application show that fluctuations in temperature between mesophilic and thermophilic environments is indeed possible without any loss in biogas production performance. This would be particularly favourable because the digester can thus act as a heat storage. In order to validate temperature fluctuations on full-scale digesters the data of two digesters from different wastewater treatment plants (WWTPs) with high temperature fluctuations were analyzed. In addition, chemical oxygen demand (COD) balances for different temperature ranges were conducted in order to evaluate the process stability. The results show that fluctuations between mesophilic and thermophilic conditions can be achieved without a decrease in biogas production. Increasing the temperature above 50 °C leads to an increase in organic acid concentration as described in the literature. Nevertheless, the total concentration of organic acid was still at an uncritical level below 500 mg/L. The COD balance shows no significant difference between 38 °C, 44 °C and 51 °C. The rate of temperature fluctuations per day specifically seems to be a main factor for process stability rather than temperature itself.

Key words: biogas, co-digestion, digestion, heat storage, sewage sludge, temperature

INTRODUCTION

From an energy point of view, anaerobic sewage sludge treatment (digestion) becomes increasingly important, as electricity and heat can be generated using biogas. The used sewage sludge is then assessed as climate-neutral, in terms of ‘renewable raw materials’. Although the focus is often set on optimizing electrical power consumption, from an ecological perspective heat must be considered in favor of efficient energy management of wastewater treatment plants (WWTPs) as well. In this context, the digester could be used as a heat storage.

Anaerobic digestion involves different process steps in which different microbial cultures interact synergistically with individual temperature optima (Tchobanoglous 2003). Mesophilic acidifying bacteria have an optimum of about 35 °C, while mesophilic methanizing bacteria reach their optimum in a range between 30 and 40 °C (Bischofsberger 2005). A mesophilic municipal sewage sludge stabilization temperature around 37 °C therefore meets various optima and is thus widely recommended in the literature (Tchobanoglous 2003; Bischofsberger 2005). For thermophilic organisms a temperature between 50–55 °C is suggested (Batstone *et al.* 2002; Bischofsberger 2005). The dependence on

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temperature of different groups of organisms follows the Arrhenius equation until reaching the respective optimum. Afterwards the activity quickly drops to zero (Batstone *et al.* 2002). In addition to microbial activity, temperature has an influence on various physiochemical processes that can have an impact on the stability of anaerobic processes (Appels *et al.* 2008). For instance, there is an increase in free ammonia concentration, causing inhibition at high temperatures (Chen *et al.* 2008; El Hadj *et al.* 2009; Yenigün & Demirel 2013).

Labatut *et al.* (2014) analyzed the process stability of thermophilic and mesophilic systems. In the experiments, the hydraulic retention time (HRT), the organic load and chemical composition were varied. Thermophilic systems are more likely to accumulate long-chain fatty acids in terms of operational fluctuations than mesophilic systems. The transition between mesophilic and thermophilic range is between 42 and 50 °C. In this temperature range a decline in the productivity of microorganisms is described with a corresponding drop in methane production and an increasing instability of the process (Zoetemeyer *et al.* 1982; Bischofsberger 2005). In contrast, Rossol *et al.* (2005) operated a reactor at 42 °C. The authors neither observed a significant drop in the pH value nor an increase in organic acids. In preliminary experiments, a stable operation up to a temperature of 45 °C was still possible. Further investigations confirm the possibility of a temperature increase to over 40 °C and more (Ortega *et al.* 2008; Bolzonella *et al.* 2012; Cavinato *et al.* 2013).

The rate at which the temperature changes, and thus the adaptation time of the bacteria to the new conditions, have a significant influence on the activity behavior of the microorganisms. Rossol *et al.* (2005) reported a rate of 2 K/week for the operation of mesophilic systems as unproblematic. Furthermore, the importance of an adaptation time with regard to a constant gas yield and gas quality was described by different authors, cf. Ortega *et al.* (2008). Boušková *et al.* (2005) compared direct heating from 37 °C to 55 °C within 24 hours with a gradual increase in temperature within 43 days. With the instantaneous increase, a decrease in gas production and a decrease in methane concentration could be observed. Similar observations were made with the gradual increase of temperature, but the decrease was significantly lower compared to direct heating. The reactor in which the temperature was instantly increased achieved stable operation within 29 days. The other reactor reached a similar gas production level after 57 days. Internationally it is recommended to avoid temperature fluctuations higher than 1 K/d. For stable digester operation temperature fluctuations higher than 0.5 K/d (WEF 2010) and 0.6 K/d should be avoided (Turovskiy & Mathai 2006; Appels *et al.* 2008).

In this study the operation data of two different municipal WWTPs were analyzed. The aim was to investigate the influence of temperature and temperature fluctuations on the performance of the reactors and to compare the results with the data given in the literature. Furthermore, a COD balance for specific periods with different temperature averages was conducted to compare the degree of degradation and derive process stability for different temperatures.

MATERIALS AND METHODS

The operating data of two municipal WWTPs were analyzed:

#WWTP_A: Municipal WWTP with a capacity of 95,000 population equivalent (PE), consisting of mechanical and biological wastewater treatment. The sewage sludge treatment has a mechanical waste activated sludge thickener and a digestion system with two digesters, each having a volume of 2,800 m^3. The digestion mainly takes place in the stirred and temperated first digester (#WWTP_A_D1). The second digester (#WWTP_A_D2) acts more or less as a storage tank contributing less than 4% to the total biogas yield. Furthermore, there is dewatering by centrifuges and a drying process. In addition to the sewage sludge produced during wastewater treatment (primary and waste activated sludge), external substrates are co-digested, which ensures electrical

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self-sufficiency of the WWTP of more than 100%. There are no emergency coolers integrated, so all heat from the combined heat and power plants has to be used within the WWTP. The data between 2012 and 2016 were evaluated.

#WWTP_B: Municipal WWTP with a capacity of 50,000 PE, consisting of mechanical and biological wastewater treatment. The sewage sludge treatment has a mechanical waste activated thickener and digestion system with two digesters, each having a volume of 1,430 m^3. The digestion mainly takes place in the stirred and temperated first digester (#WWTP_B_D1), the second digester (#WWTP_B_D2) acting more or less as a storage tank. In addition, there is a dewatering system. The data of the year 2017 were evaluated.

The data from both WWTPs were recorded either by on-line measurements according to state of the art techniques, or according to the analytical methods specified by the German Institute for Standardization (DIN). For the analysis of COD, recommendations by Schaum *et al.* (2016) were complied with. Table 1 gives an overview of the measured parameters.

Table 1 | Recorded and measured parameters

	Parameter	Unit
Input digester	Q_{input}	m^3/d
	$Q_{co\text{-}substrate}$	m^3/d
	COD_{input}	mg/L
	TS	%
	TVS	%
Biogas	Q_{biogas}	m^3/d
	c_{CH4}	%
	c_{CO2}	%
Output digester	Q_{output}	m^3/d
	TS	%
	TVS	%
	COD_{output}	mg/L
	PO_4-P	mg/L
	NH_4-N	mg/L
	oHAC	mg/L

Taking the digester volume of 2,800 m^3 into account (neglecting the digestion performance of #WWTP_A_D2), a specific volume load of 2.45 kg COD/(m^3·d) is calculated for #WWTP_A_D1. According to DWA (2014), a volume load of 1.8–2.6 kg COD/(m^3·d) is recommended for a WWTP the size of 50,000–100,000 PE. For two-stage digestion systems, volume loads for the first stage between 5.4–7.1 kg COD/(m^3·d) are recommended (DWA 2014). This shows that the digester is already operated with a high volume load, especially when it is considered that the co-substrate addition was added as a shock charge (the volume load can be up to 3.5 kg COD/(m^3·d)). The hydraulic retention time (HRT) was 20 days during the period of observation. In addition to the raw sludge, organic residues from biodiesel (COD = 100–300 g/L; TS < 1%) and food production (COD = 30–50 g/L; TS < 1%) was fed into the digester. Co-substrates contributed 16% to the total input. This corresponds to a share on the COD load of around 0.5 kg $COD_{Co\text{-}Substrates}$/($m^3$·d). The specific gas production is due to the co-substrates with approx. 50 L/(PE·d) above the average digester gas production of 25 L/(PE·d) according to DWA (2015) for municipal WWTPs.

#WWTPB_D1 was operated with a COD load of 1.3 kg COD/(m^3·d), respectively 0.4 kg total volatile solids (TVS)/(m^3·d). The organic load was thus far below the recommended values of 1.9 to 2.5 kg

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TVS/(m^3·d) for the size of digester (WEF 2010). The HRT was 28 days for #WWTP_B_D1. In addition to the raw sludge, fats from nearby grease traps are co-digested within the digester. Co-substrates contribute 1% to the total input, contributing only 0.03 kg COD/(m^3·d) to the COD load. The specific gas production for the period under review is 30 L/(PE·d). This is slightly above the average biogas production of 25 L/(PE·d) for WWTPs according to DWA (2015).

In order to compare the degradation efficiency of different temperature ranges, as well as to evaluate process stability using co-substrates in the digester, COD balances were conducted for #WWTP_A_D1. In addition to a two-year balance, three different periods with different temperature ranges were identified and balanced.

COD_{input} load and COD_{output} load per day (kg COD/d) were calculated according to Equations (1) and (2).

$$B_{COD,input} = \sum_{i=1}^{t} (Q_{input,i} \cdot TS_i \cdot TVS_i \cdot f_i)_i \tag{1}$$

$$B_{COD,output} = \sum_{i=1}^{t} (Q_{output,i} \cdot TS_i \cdot TVS_i \cdot f_i)_i \tag{2}$$

With Q being the flow (m^3/d) and f being the specific COD/TVS ratio (g/g) for the respective substrate, assuming a COD/TVS ratio of 1.56 g/g for primary sludge, 1.46 g/g for waste activated sludge and 1.48 g/g for digested sludge according to Schaum (2016).

The degraded COD load is calculated by subtracting the $B_{COD,output}$ from the $B_{COD,input}$ (Equation (3)).

$$B_{COD,degraded} = B_{COD,input} - B_{COD,output} \tag{3}$$

For a plausibility check, the resulting digester gas was converted into a COD load. The calculation is done according to formula [4].

$$B_{COD,biogas} = \frac{Q_{biogas} \cdot c_{methane}}{s} \tag{4}$$

With $s = 0.32\ m^3\ CH_4$/kg $COD_{degraded}$ (specific methane production according to VDI 4630 (2006) assuming that 10% of the COD load contributes to the generation of biomass and 1 g of COD equals 350 Nml CH_4, cf. Tchobanoglous (2003)).

The plausibility check is carried out by calculating the deviation between $COD_{degraded}$ and COD_{biogas} loads according to the formula [5].

$$\text{variance} = \frac{B_{COD,biogas} - B_{COD,degraded}}{B_{COD,biogas}} \tag{5}$$

RESULTS AND DISCUSSION

Temperature profile of #WWTP_A_D1 und #WWTP_B_D1

The temperature curves of #WWTP_A_D1 and #WWTP_B_D1 are shown in Figures 1 and 2. The characteristic curves were smoothed by calculation of a 14-day-average for a better representation and comparability. In #WWTP_A_D1, the average temperature during the observation period was 41.8 °C, which was above the recommended temperature of 37 °C for mesophilic digestion in the

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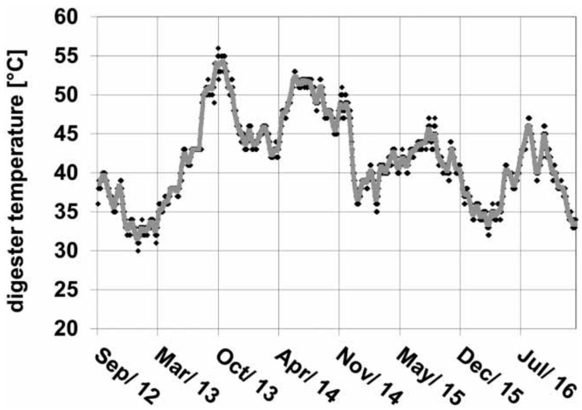

Figure 1 | Temperature #WWTP_A_D1.

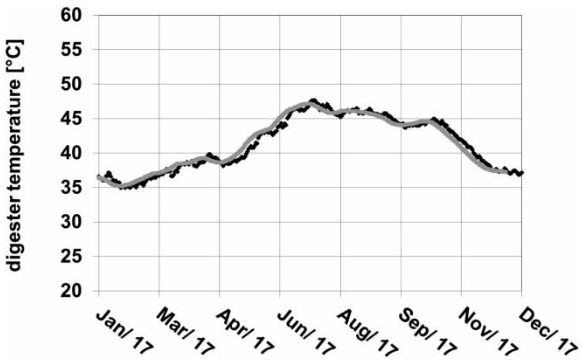

Figure 2 | Temperature #WWTP_B_D1.

literature. Maximum and minimum temperature were 56 °C and 30 °C respectively. The average temperature was 41.1 °C for #WWTP_B_D1. Maximum temperature was 48 °C and minimum was 35 °C.

Temperature change per day

Despite high temperature fluctuations, the rate of heating or cooling was below 0.7 K/d in the observed period for #WWTP_A and 1.0 K/d for #WWTP_B (cf. Figures 3 and 4), and thus didn't exceed the critical value of 1.0 K/d according to WEF (2010). In most instances, temperature changes were even below 0.5 K/d for both WWTPs.

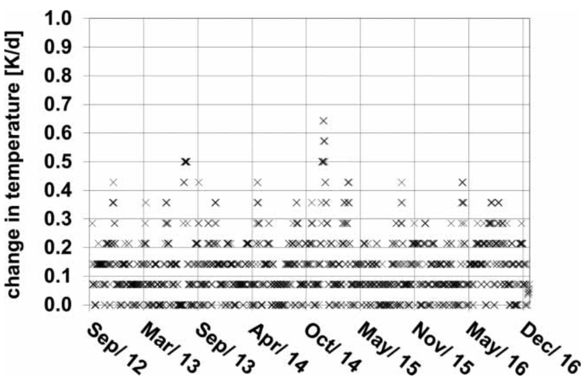

Figure 3 | Temperature change per day in #WWTP_A_D1.

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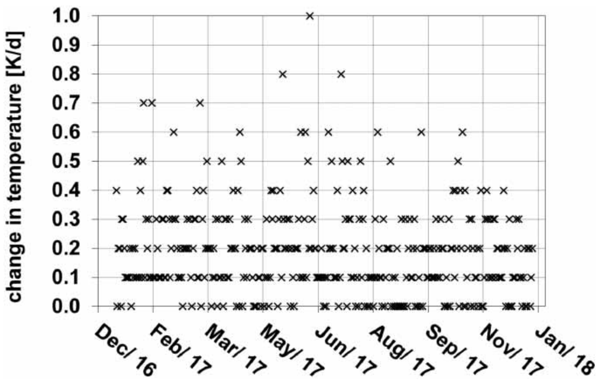

Figure 4 | Temperature change per day in #WWTP_B_D1.

Figures 5 and 6 show the relationship between the biogas produced and the temperature in the digesters for both WWTPs. No significant change in biogas production can be identified in both diagrams. This contradicts the general assumption that microbiological activity decreases between 40 and 50 °C and reduces the biogas production, cf. Bischofsberger (2005). With regard to the gas quality, no correlation between temperature and biogas quality could be observed, cf. Figures 7 and 8. The methane concentration during the period of observation was 63% on average for #WWTP_A and 70% for #WWTP_B.

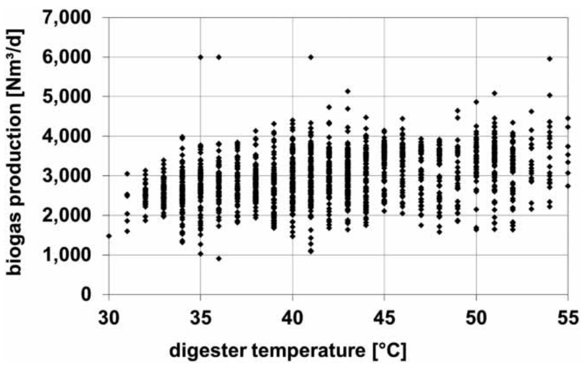

Figure 5 | Relationship between biogas production and temperature for #WWTP_A.

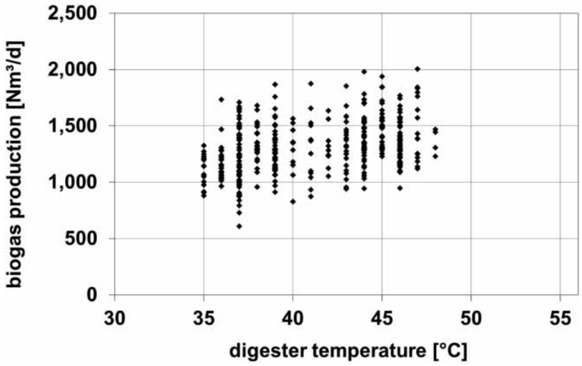

Figure 6 | Relationship between biogas production and temperature for #WWTP_B.

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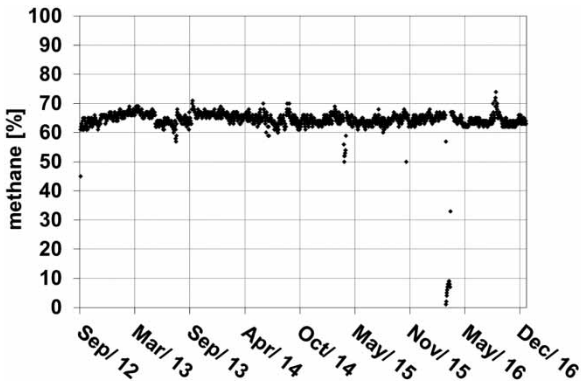

Figure 7 | Methane concentration of #WWTP_A.

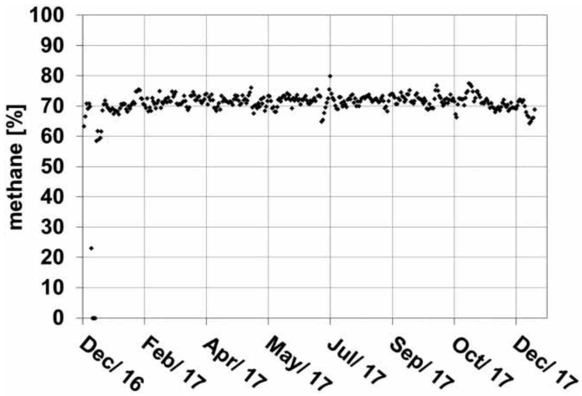

Figure 8 | Methane concentration of #WWTP_B.

COD-balance for #WWTP_A_D1

Conventionally, digesters are balanced and dimensioned via the TVS loading rate (TVS/(m^3·d)) and the sludge retention time (WEF 2010). This is applicable, if the substrates have a COD/TVS ratio comparable to sewage sludge. As soon as co-substrates vary from this value, like in the case of #WWTP_A, this way of balancing is no longer applicable (Zeig 2014; Lensch *et al.* 2015; Schaum 2016). In this case, a balance based on COD or TOC should be preferred.

One problem with COD balancing is the lack of analytical data. In particular, the lack of representative analysis of COD in sewage sludge and co-substrate samples is a problem, cf. Schaum *et al.* (2016). In this study, missing analytical data regarding the composition of the co-substrates represented a problem, so that further COD analyses were carried out. The plausibility checks regarding the quantity of sewage sludge disposed and the comparison with literature values (COD/TVS ratio and specific methane production of the degraded COD) were conclusive, so an adequate accuracy of the balancing can be assumed.

The COD balance was conducted for a period of two years between 01/01/2014 and 12/31/2015 as well as for the periods between January and March 2015 with an average temperature of 38 °C (mesophilic), between June and September 2014 with an average temperature of 51 °C (thermophilic) and finally between January and May 2014 with an average temperature of 44 °C, cf. Figure 9. 44 °C represents a transition region between mesophilic and thermophilic environments and thus is of particular interest. According to the doctrine, a reduction in anaerobic degradation processes in the digester is to be assumed in this temperature range due to lower bacterial activity. However, the diagrams did not show the patterns expected.

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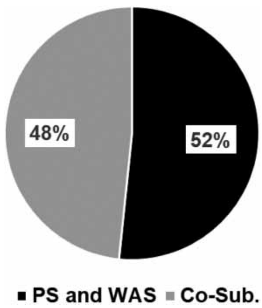

Figure 9 | Percentage of substrates on biogas production for WWTP_A.

Figure 10 shows the percentages of raw sludge and co-substrates on the total gas production based on estimations of the specific gas production of the individual substrates (assuming a specific gas production of primary sludge of 0.57 m^3/kg TVS_{input} and waste activated sludge (WAS) of 0.33 m^3/kg TVS_{input}, cf. DWA (2014); proportion of co-substrates on gas production calculated by the subtraction of the proportion of primary sludge (PS) and WAS from the measured gas production). The percentage of co-substrate is with 50% on a high level. This again illustrates the need for balancing on the basis of the COD, since the substrates differ significantly from the composition of sewage sludge.

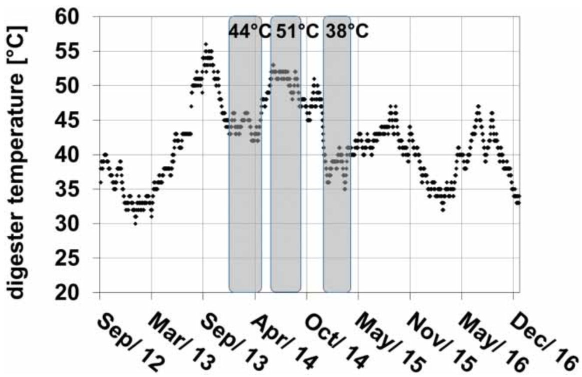

Figure 10 | Identified temperature ranges of #WWTP_A.

Figure 11 shows the results of the COD balance for the evaluated periods. The COD_{input} load in the influent of #WWTP_A_D1 is similar for all considered periods. Although, there are some deviations there is also a similarity given for the degradable $COD_{degraded}$ load. Figure 11 also shows the biogas quantity converted to a COD_{biogas} load. The comparison of the calculated $COD_{degraded}$ load and the measured digester gas equivalent (COD_{biogas}) shows a deviation of 0 to 20%. Taking the

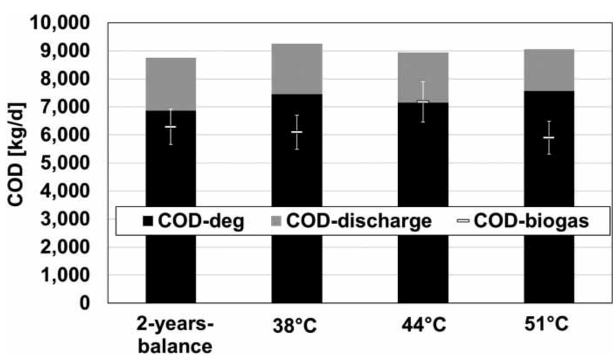

Figure 11 | Results of the COD balancing of the different periods #WWTP_A.

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corresponding uncertainties (assumption of 10%) into account, no significant effect of the temperatures on the gas production can be demonstrated overall. Especially since the total uncertainties resulting from the measurement and analysis in the field of sewage sludge treatment might have overlapping effects.

Process stability

The stability of the process was evaluated by the parameters of methane concentration in digester gas, ammonium and organic acids concentration in the sludge liquor as well as the pH value in the digester. However, analysis of NH_4-N and organic acids in the sludge liquor were only available for #WWTP_A_D1.

Concerning the methane content, there was no significant change in both WWTPs over the period considered, cf. Figures 7 and 8. The methane content was always above 60% throughout the timescale.

In terms of organic acids concentration, only a minor dependency on the temperature profile could be identified for digester #WWTP_A_D1, cf. Figure 12. Between June and September 2014 the average temperature was 51 °C and thus considerably above the average temperature of the entire observation period (41.8 °C). According to the literature, an increase in the concentration of organic acids should be observed. On average, the concentration of organic acids between June and September 2014 was 245 mg/L, with a maximum at 380 mg/L. The average value is slightly above the value of 179 mg/L for the total observation period. In the period between January and May 2014, the temperature averaged 44 °C and was therefore in a transition region between the mesophilic and thermophilic range. Nevertheless, the organic acid concentration was at a low level and averaged 208 mg/L. Maximum organic acid concentration was at 490 mg/L and minimum at 140 mg/L.

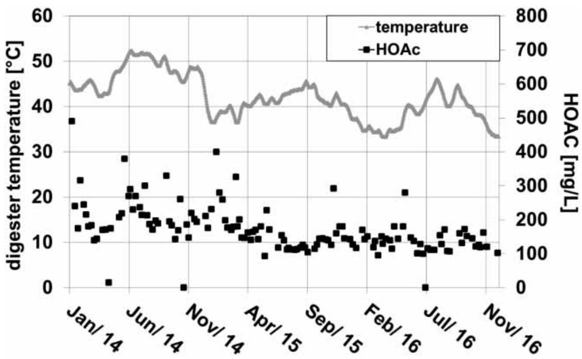

Figure 12 | Organic acid concentration in digester of #WWTP_A_D1.

However, in the literature, a significantly higher increase in organic acid concentration is described with temperatures increasing above 38 °C. Lensch (2015) described a significant increase in organic acids during the operation of different digesters in a 15 L scale. Organic acid concentration increased gradually, while increasing temperature from 37 °C to 42 °C, 37 °C to 45 °C and 37 °C to 50 °C. Lensch (2015) also observed an increasing amount of NH_4-N and PO_4-P during the experiments caused by increased hydrolysis at higher temperatures. Nevertheless, the concentration of dissolved substances was the highest for a temperature of 45 °C. Neither a higher organic acid concentration nor a higher concentration in dissolved substances could be confirmed for #WWTP_A_D1. The concentration of NH_4-N in the sludge liquor of the digester showed no correlation with the temperature, cf. Figure 13. Effects appear rather to be superimposed by the addition of co-substrates and the volumetric load.

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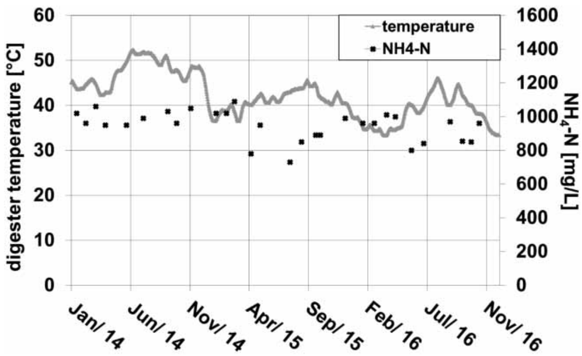

Figure 13 | Ammonium concentration in #WWTP_A_D1.

CONCLUSIONS

The data analysis showed that the operation of digesters between mesophilic and thermophilic temperatures is basically possible. During the period of observation there were no significant correlations between the temperature and the parameters methane concentration, gas production, organic acids and NH_4-N in the sludge liquor. Heating the digester above a temperature of 50 °C led to a slight increase in organic acid concentration, nevertheless it never exceeded a value of 500 mg/L. Throughout the time of observation biogas production was around 3,000 Nm^3/d. Strongly diverging values did not correlate to temperature or temperature changes.

In particular, the rate of temperature change seems to have a more significant influence on the digestion process than the temperature itself. During the observation period, critical values described in the literature for the operation of digesters were never exceeded. The maximum temperature change during the observation period was 0.7 and 1 K/d respectively for #WWTP_A_D1 and #WWTP_B_D1.

According to those findings, the use of the digester as a heat storage is possible and is already practiced, at least in those plants analyzed within this research. The stored heat leads to reduced time of active heating in the analyzed plants, which results in less energy consumption. Furthermore, the use of emergency coolers can be dispensed with. Nevertheless, due to higher temperature differences and the resulting stresses, the statics of the digesters must be checked in advance. If designed appropriately the digester can be implemented in a heat management system within the WWTP, leading to an overall improved energy balance

In future, it should be examined to which extent a switching to thermophilic conditions is possible, if heat is abundant. The resulting higher digester capacities due to reduced HRT could be used for co-digestion of high energetic organic residues from external facilities (e.g. food or beverage industry) and thus increase biogas production. The increased gas production can contribute to achieve energy self-sufficiency or even allow WWTPs to participate on the energy market.

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