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RESEARCH ARTICLE

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Digesters as heat storage: Effects of the digester temperature on the process stability, sludge liquor quality, and the dewaterability

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Abstract

Variation of the digester temperature during the year enables the operation of digesters as seasonal heat storage contributing to a holistic heat management at water resource recovery facilities. Full- and lab-scale process data were conducted to examine the effect of the digester temperature on process stability, sludge liquor quality, and dewaterability. Both full- and lab-scale digesters show a stable anaerobic degradation process with a hydraulic retention time of more than 20 days and organic load rates up to 2.2-kg COD/(m^3·day) at temperatures between 33 and 53°C. The concentrations of soluble COD and ammonium-nitrogen in the sludge liquor digested at 53°C are 2.6 to 5.8 times and 1.3 times higher, respectively, than in the sludge liquor digested at 37°C. Dewatering tests show an enhancement of the dewaterability but a clear increase in the polymer demand at increased digester temperature.

Practitioner Points

- Digesters can operate as seasonal heat storage within mesophilic and thermophilic temperatures
- Stable anaerobic degradation process for HRT above 20 days
- Maintenance of process stability as well as quantity and quality of biogas
- Increase of soluble COD in sludge liquor at higher temperatures
- Better dewaterability but higher demand for polymers with increasing temperature

KEYWORDS

anaerobic digestion, biogas, mesophilic, process stability, sludge dewatering, sludge liquor, thermophilic

INTRODUCTION

Digester temperature is one, if not the most, relevant aspect of anaerobic sludge stabilization in water resource recovery facilities (WRRF). Beyond the main objective of sludge stabilization, digesters can contribute to a holistic heat management at WRRFs by acting as seasonal heat storage, increasing the digester temperature to store excessive heat and decreasing the digester temperature to compensate heat deficits (DWA, 2014; Steiniger et al., 2021). Hubert et al. (2019) and Loidl (2020) reported seasonal adjustment of the digester temperature between 33 and 53°C for three WRRFs in Central Europe, suggesting that no inactivation of methane-producing bacteria occurs at temperatures in the mesophilic and thermophilic range when temperature gradients are kept to a minimum.

Although an increase in digester temperature accelerates biochemical and enzymatic processes in bacterial cells, there is a temperature optimum for bacteria that, if exceeded, leads to inactivation of the metabolism (Madigan et al., 2010). The digester temperature is usually set to optimal environmental conditions for certain microorganisms, especially temperature-sensitive methanogens, which carry out the anaerobic degradation process. Therefore, digesters are operated at constant temperature levels, mostly at mesophilic temperatures between 30 and 40°C, typically at 37°C, and rarely at thermophilic conditions between 50 and 55°C (de Lemos Chernicharo, 2007; DWA, 2014; Roediger et al., 1990; Tchobanoglous, 2014). On the contrary, the minimum required digestion time is shown as a continuously decreasing curve depending on the digester temperature, even between 40 and 50°C (Bauerfeld, 2012; DWA, 2014).

Research investigating the kinetics, methane content, dewaterability, and sludge liquor quality that focus on the comparison between mesophilic and thermophilic temperatures appear partially contradictory. On the one hand, some studies announced that these parameters are dependent on certain anaerobic process conditions such as hydraulic retention time (HRT), organic loading rates (OLR), and temperature constancy. On the other hand, several publications reported no significant changes in specific methane yields between the temperature optima of mesophilic and thermophilic temperatures (Lüdtke et al., 2018; Mieske, 2018; Temper, 1983; Wilson et al., 2008).

The methane content in biogas is mainly dependent on the organic compounds such as fats, lipids, and carbohydrates in the fed substrates, whereby a decrease in methane or an increase in carbon dioxide is an indicator of instabilities during the anaerobic degradation process (VDI, 2016). The comparison of methane contents at mesophilic and thermophilic temperatures are mostly described as identical (de la Rubia et al., 2005; Kabouris et al., 2009; Pfeiffer, 1990; Rimkus et al., 1982) or occasionally as higher at mesophilic temperatures (Chi et al., 2010; Lin et al., 1987; Song et al., 2004). Between mesophilic and thermophilic temperatures, identical methane contents are reported by Zabranska et al. (2002), de la Rubia et al. (2005), and Lensch (2018).

Digester temperature is one of the essential environmental conditions of the biocenosis, in particular the methanogens, which ensures process stability and sludge stabilization. To achieve stable conditions, de la Rubia et al. (2005), de Lemos Chernicharo (2007), and WEF (2018) suggested that the temperature changes should be below the range of 0.5 to 2.5 K per day, whereas Rossol et al. (2005) and DWA (2014) suggested 2 to 5 K per week. However, already short-term temperature changes can cause process disturbances (Bischofsberger et al., 2005; Buhr & Andrews, 1977). Notwithstanding the previous, organic acid concentrations are increasing with the digester temperature (Buhr & Andrews, 1977; de la Rubia et al., 2002; Pfeiffer, 1990; WEF, 2018). Further, an increased digester temperature influences the ammonia and ammonium equilibrium. Temperature-induced inhibition of methane production by free ammonia can occur, especially when protein-rich (co)substrates are fed at thermophilic temperatures (Kroeker et al., 1979; Pfeiffer, 1990). In total, mesophilic temperatures are considered more stable, not least because of the higher biodiversity of the biocenosis in comparison to thermophilic temperatures (Bischofsberger et al., 2005; Hupfauf et al., 2020).

The effect of the digester temperature on the concentrations of soluble compounds in sludge liquor, such as soluble COD and ammonium, provides both insights into process stability and an assessment of the back loads into the WRRF. At thermophilic temperatures, concentrations of soluble chemical oxygen demand (COD) are 1.5 to 3 times higher than at mesophilic temperatures (Kabouris et al., 2009; Moen et al., 2003; Temper, 1983) or even significantly higher (Garber et al., 1975; Malý & Fadrus, 1971; Zeig, 2013). In addition, the ammonium concentrations are either constant (Temper, 1983) or higher (Chi et al., 2010; Garber et al., 1975; Kapp, 1985; Malý & Fadrus, 1971; Zeig, 2013) at thermophilic than at mesophilic temperatures. Higher ammonium concentrations can be traced back to the proceeding degradation of protein compounds. However, the increase in soluble COD from mesophilic to thermophilic temperature is expected to be higher than that of ammonium.

The temperature plays a dual function in sludge dewatering. Both the digester temperature and the sludge temperature during dewatering can influence the dewatering result due to changes in viscosity, particle size distribution, and the release of water-binding compounds

(DWA, 2014, 2019). However, increasing the temperature during the dewatering process and pre-heated water for flocculation can enhance the dewaterability due to lower viscosity (Denkert, 2015). In particular, water-binding extracellular polymeric substances (EPS) influence the dewatering result, as these mainly contain complexes of long-chain polysaccharides, proteins, hydroxy, and negatively charged carboxyl groups (Higgins & Novak, 1997). Bouskova et al. (2006) reported enhanced dewaterability in compression but deterioration of dewaterability in filtration tests with sludges digested at 33, 35, 37, 39, and 55°C, as well as an increase in dissolved EPS with increasing digester temperature. Further, Rossol et al. (2005) demonstrated a significantly poorer dewatering result at the same polymer quantity for 42°C in comparison to 37°C.

The concept of using digesters as seasonal heat storage in temperate climates has already been considered from an energy perspective by Steiniger et al. (2021). In addition, the objective of this study is to assess the effects of digesters operated at temperatures between 33 and 53°C on the biogas quantity and methane content, process stability, sludge stabilization, sludge liquor composition, and sludge dewatering based on full-scale process data and additional lab-scale experiments.

MATERIAL AND METHODS

Digester design at WRRF

Process data of three municipal WRRFs in Germany consisting of comparable basic process technology with mechanical and biological wastewater treatment (denitrification and nitrification) were analyzed. These site-specific boundary conditions characterize each WRRF:

- WRRF #A: 95,000 population equivalent (PE). Two egg-shaped digesters are connected in series with predominant gas production in the first digester (here considered as a single-stage digester with 2800 m^3 because the second digester is operated as a storage tank without heating and mixing). The average HRT in the first digester is around 28 days. Primary sludge (evenly distributed feeding throughout the day), secondary sludge, and co-substrates (feeding depending on the level of the pre-thickener and the gas storage tank) are fed as substrates to the digesters. The digesters are heated via a heat exchanger with a sludge circulation line. Evaluated process data from 2012 to 2020 contain digester temperatures between 30 and 56°C.
- WRRF #B: 50,000 PE. Two egg-shaped digesters with 1430 m^3 are connected in series with predominant gas production in the first digester (here considered as a single-stage digester because the second digester is operated as a storage tank without heating and mixing). The average HRT in the first digester is around 35 days. The digesters are fed with primary sludge (semi-continuously fed up to 6 times a day as shock load), secondary sludge (continuously fed), and external grease trap (feeding depending on the frequency of delivery up to 2 times a week; feeding together with the primary sludge). Digesters are heated via a heat exchanger with a sludge circulation line. Evaluated process data from 2017 to 2020 contain digester temperatures between 33 and 50°C.
- WRRF #C: 35,000 PE. Two single-stage digesters with 1500 m^3 each are operated in parallel mode. Digesters are fed with primary sludge (semi-continuously fed throughout the day) and secondary sludge (continuously fed). One digester is constructed as a cylinder and the other one as an egg. The average HRT in each digester is 38 days. Both digesters are heated via a heat exchanger with a sludge circulation line. Evaluated process data from 2016 to 2019 contain digester temperatures between 33 and 44°C.

As the process data from the WRRFs is limited, data from full-scale digesters are used to determine specific methane yields, methane contents, COD elimination rates, and volatile fatty acids (VFA) concentrations. In addition to the available process data, gas composition of WRRF #B was determined using micro gas chromatography (GC). An overview of process data from the three WRRFs to describe the effects of digester temperatures between 33 and 53°C on the anaerobic degradation process and the outgoing flows of biogas and biosolids is presented in Figure 1.

Experimental set-up of the lab-scale digesters

Four to five cylindrical lab-scale digesters, respectively, with 15 and 25 L working volumes each were operated from 2019 to 2022 with the same process conditions regarding the substrate, HRT, and feeding interval. Each digester is heated via a heating mat. All reactors were fed with a mixture of primary and secondary sludge (PS:SS) from WRRF #B with 50:50%w/w once a day as shock load either for 5 or 6 days a week. Moreover, the HRT was 20 days in each reactor. Table 1 summarizes the main operation conditions for these experiments. The presented data is an extract of five periods of the total experiment period with detailed additional analytics. One digester each was maintained at 37, 43, 47, and

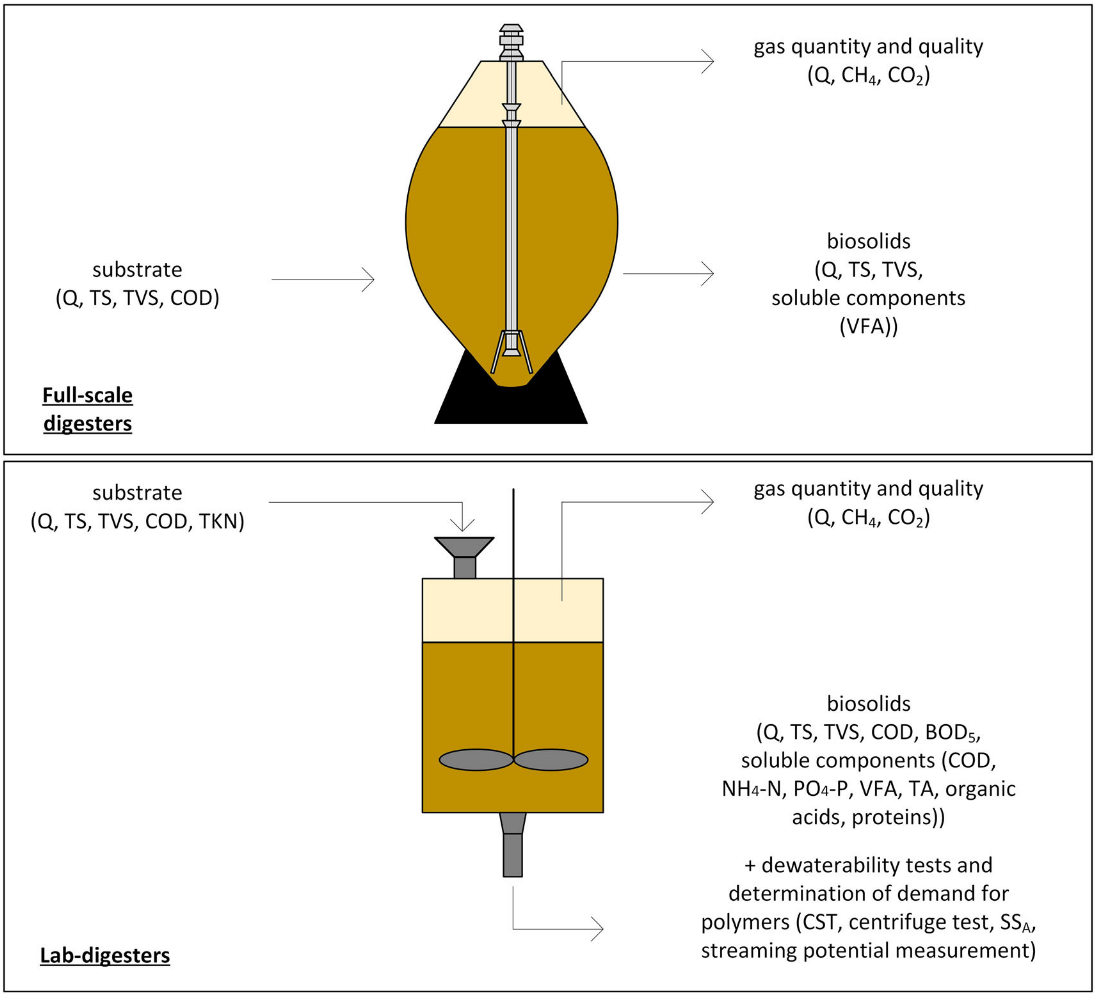

FIGURE 1 Overview of process data, measurements and analytics of substrate, gas and biosolids from full- and lab-scale digesters (full-scale samples for analysis were taken from recirculation pipe; parameters were directly analyzed after sampling; volume flow [Q], total solids [TS], volatile solids [TVS], chemical oxygen demand [COD], total Kjeldahl nitrogen [TKN], biochemical oxygen demand after 5 days [BOD_5], volatile fatty acids [VFA], total alkalinity [TA], organic acids [C2 to C6]).

TABLE 1 Operation of digesters and characterization of fed raw sludges (average for all PS:SS mixtures).

Parameter	Unit	PS:SS #1	PS:SS #2	PS:SS #3	PS:SS #4	PS:SS #5	PS:SS[a]
Amount of digesters	-	4	4	5	5	4	-
Temperature	°C	37, 43, 47, 53		33, 37, 43, 47, 53		37, 43, 47, 53	-
HRT	Day	20	20	20	20	20	
Feeding period	Day	21	25	28	29	22	25.0 ± 3.5
Feeding events[b]	-	5/7	5/7	5/7	6/7	6/7	-
TS	%	6.2	4.2	3.9	5.1	4.5	4.8 ± 0.9
TVS	%	66.0	71.6	80.0	80.0	84.0	76.3 ± 7.3
COD	mg/L	60,900	45,600	47,700	53,300	50,800	51,660 ± 5,942
COD/TS	g COD/kg TS	982	1,086	1,223	1,045	1,141	1,093 ± 91
TKN	mg/L	2,600	2,300	2,200	2,700	3,200	2,599 ± 392
TKN/TS	g TKN/kg TS	42	55	58	53	71	55 ± 11

[a]Average and standard deviation.
[b]Times per week.

53°C for PS:SS #1, #2, and #5 and at 33, 37, 43, 47, and 53°C for PS:SS #3 and #4.

Detailed characterization of fed substrate mixtures is based on TS, TVS, COD, and TKN as shown in Table 1. The substrate mixtures were frozen and thawed before feeding. Each substrate mixture was fed for at least one HRT. The temperature adaption to each level took four HRT before data evaluation of the selected periods.

Furthermore, the gas quantity, TS, and TVS of the lab-scale digesters were determined daily, and the gas composition and parameters for biosolids characterization were measured once a week. TS and TVS were gravimetrically analyzed by drying at 105°C and subsequent burning at 550°C. In addition, TVS is calculated as volatile solids of the TS. The gas composition was determined by a micro GC (Agilent Technologies 490 Micro GC, Santa Clara, California) and the gas quantity with an online gas meter each 15 min (Ritter TG 0.5, Bochum, Germany). The gas quantities were normalized to standard temperature and pressure conditions and corrected with the Magnus formula considering the water vapor pressure (VDI, 2016). COD (total and soluble), NH_4-N, PO_4-P, and organic acids (C2 to C6) were analyzed once a week. Determination of concentrations of VFA, TA and proteins, dewaterability tests, and polymer demand took place at the end of selected periods of PS:SS mixtures. An overview of the process data from the lab-scale experiments and a further analysis of the outgoing flows of biogas and biosolids are presented in Figure 1.

Physico-chemical methods

TS and TVS were gravimetrically analyzed after drying at 105°C and burning at 550°C according to the recommendations of the APHA Standard methods. COD was analyzed using cell tests (Spectroquant, Merck, Darmstadt, Germany) complying with the recommendations of Schaum et al. (2016). Moreover, for the determination of soluble components, samples were filtrated with a 0.45-μm syringe filter. PO_4-P and NH_4-N were analyzed using a continuous flow analyzer (CFA, Bran+Luebbe Auto Analyzer III. Norderstedt, Germany). Organic acids (C2 to C6) were measured using GC (Agilent Technologies 6890N; capillary column Agilent J&W HP-FFAP, Santa Clara, California). VFA and TA were analyzed after centrifuging the samples for 15 min at 12,500 rpm (TitraLab AT1000 Series; Hach Lange GmbH, Düsseldorf, Germany) using sulfuric acid (0.1 N). Measurements of BOD_5 (WTW Oxitop ® OC 110) were used to determine BOD_5/COD ratios.

Dewaterability tests were conducted for PS:SS #5 at the end of the feeding period after samples cooled down to the ambient temperature. Soluble proteins were determined following the Bradford protein assay in comparison with the standard bovine serum albumin (Bradford, 1976). Capillary suction tests (CST) were carried out using the Triton–W.P.R.L. Type 92/1 apparatus. CST results were standardized to the TS of the original sample and presented as specific CST (sCST) in s/%. Centrifuge tests were conducted with samples centrifugated for 15 min at 12,500 rpm, which is based on the recommendations by DWA (2019). Additionally, both the solid content after separation of the free water (SS_A) by thermogravimetric measurement and the polymer demand (with 9148FS, Zetag ®) by streaming potential measurements were analyzed following the procedure and recommendations of Kopp and Dichtl (2001) and DWA (2019). Results of the polymer demand are given in the unit based on active substance (AS) as kg AS/Mg TS.

COD balancing of full- and lab-scale digesters

To evaluate constant temperature levels between 33 and 53°C from the pronounced temperature profiles of the full-scale digesters, periods with digester temperatures of 34, 37, 40, 43, 46, 49, and 52°C and temperature gradients below ± 1 K for at least 1 month were evaluated. Because of the seasonal variation of the digester temperature at each WRRF, amounts of data sets differ for each temperature level (cf. Table 2). For the lab-scale experiments, the feeding period of each PS:SS mixture was used for COD balancing.

Following the procedure described by Hubert et al. (2019), COD balances were used to determine specific methane yields, methane contents, and COD elimination rates for process data from full- and lab-scale digesters. Taking into consideration that up to 10% of COD is used for formation of new biomass, it is assumed for calculation of COD elimination rates that 1-kg degraded COD equals 320 L_N CH_4 as the COD balance is based on added COD and produced methane (VDI, 2016). In case the data of full-scale digesters is insufficient, COD/TVS ratios were used on the basis of literature values (1.56, 1.46 and 1.48 g/g for primary, secondary, and digested sludge) by Schaum (2016).

RESULTS AND DISCUSSION

Biogas quantity and methane contents

Specific methane yields of full-scale process data vary between 218 and 256 L_N CH_4/kg COD_{added} at WRRF

TABLE 2 Results of data evaluation from COD balances from full- and lab-scale digesters for each temperature level in °C.

		Full-scale digesters				Lab digesters	
Parameter	**Unit**	**Temperature in °C**	**WRRF #A**	**WRRF #B**	**WRRF #C**	**Temperature in °C**	**PS:SS**
Specific methane yield	[L_N CH_4/kg COD_{added}]	34[a]	254.5 ± 9.1	179.6	169.1	33[b]	181.5 ± 2.9
Methane content	[%]		65.4 ± 0.8	63.1	65.7		63.5 ± 0.8
COD elimination rate	[%]		69.4 ± 2.1	57.2	64.9		60.6 ± 2.9
OLR	[kg COD/(m^3·day)]		1.5 ± 0.1	1.5	0.5		1.6 ± 0.3
HRT	[day]		23.3 ± 2.6	22.8	73.8		20.0 ± 0.4
Specific methane yield	[L_N CH_4/kg COD_{added}]	37[a]	243.1 ± 24.0	200.6 ± 16.2	170.1 ± 11.9	37[b]	199.5 ± 16.0
Methane content	[%]		64.2 ± 1.1	62.9 ± 0.3	66.2 ± 0.3		64.1 ± 1.8
COD elimination rate	[%]		67.0 ± 3.8	63.2 ± 4.2	65.1 ± 2.7		61.9 ± 5.0
OLR	[kg COD/(m^3·day)]		1.5 ± 0.2	1.5 ± 0.1	0.5 ± 0.0		1.8 ± 0.3
HRT	[day]		23.0 ± 3.5	25.8 ± 0.6	75.6 ± 0.5		19.9 ± 0.5
Specific methane yield	[L_N CH_4/kg COD_{added}]	40[a]	255.5 ± 24.7	217.6 ± 6.6	170.9 ± 6.2	-	-
Methane content	[%]		64.1 ± 1.2	63.4 ± 0.5	65.5 ± 1.2		
COD elimination rate	[%]		70.9 ± 3.5	67.1 ± 2.3	66.1 ± 1.2		
OLR	[kg COD/(m^3·day)]		1.6 ± 0.3	1.4 ± 0.1	0.5 ± 0.0		
HRT	[day]		23.9 ± 3.3	30.3 ± 1.7	74.4 ± 3.0		
Specific methane yield	[L_N CH_4/kg COD_{added}]	43[a]	247.7 ± 18.0	215.0 ± 9.7	190.2	43[b]	204.9 ± 18.4
Methane content	[%]		63.9 ± 1.4	63.1 ± 0.2	65.0		64.2 ± 1.5
COD elimination rate	[%]		70.2 ± 4.3	65.2 ± 1.5	70.2		64.1 ± 6.1
OLR	[kg COD/(m^3·day)]		1.7 ± 0.3	1.4 ± 0.1	0.5		1.6 ± 0.2
HRT	[day]		24.2 ± 3.0	26.5 ± 0.9	82.5		20.1 ± 0.5
Specific methane yield	[L_N CH_4/kg COD_{added}]	46[a]	254.4 ± 28.0	219.6 ± 12.4	-	47[b]	209.1 ± 18.3
Methane content	[%]		65.2 ± 1.0	63.6 ± 0.7			64.1 ± 1.5
COD elimination rate	[%]		72.0 ± 6.4	67.7 ± 3.8			64.2 ± 7.5
OLR	[kg COD/(m^3·day)]		1.9 ± 0.3	1.6 ± 0.1			1.8 ± 0.4
HRT	[day]		22.8 ± 3.3	28.9 ± 1.4			20.0 ± 0.3
Specific methane yield	[L_N CH_4/kg COD_{added}]	49[a]	247.0 ± 11.2	-	-	-	-
Methane content	[%]		64.4 ± 0.3				
COD elimination rate	[%]		69.0 ± 0.4				
OLR	[kg COD/(m^3·day)]		1.9 ± 0.5				
HRT	[day]		21.0 ± 0.7				
Specific methane yield	[L_N CH_4/kg COD_{added}]	52[a]	217.7 ± 14.3	-	-	53[b]	202.1 ± 21.0
Methane content	[%]		64.0 ± 0.3				64.1 ± 1.3
COD elimination rate	[%]		65.9 ± 2.8				61.3 ± 8.4
OLR	[kg COD/(m^3·day)]		2.2 ± 0.4				1.7 ± 0.3
HRT	[day]		21.2 ± 3.0				20.0 ± 0.4

[a]Amount of evaluated periods for WRRF #A, #B, and #C: 34°C (n = 3, 1, 1), 37°C (n = 4, 2, 2), 40°C (n = 12, 3, 6), 43°C (n = 9, 3, 1), 46°C (n = 4, 2, -), 49°C (n = 3, -, -), and 52°C (n = 1, -, -).
[b]Amount of evaluated periods for all PS:SS mixtures: 33°C (n = 2), 37°C (n = 5), 43°C (n = 5), 47°C (n = 5), and 53°C (n = 5).

#A, 180 and 220 L_N CH_4/kg COD_{added} at WRRF #B as well as 169 and 190 L_N CH_4/kg COD_{added} at WRRF #C (cf. Figure 2a). With increasing digester temperature, the specific methane yields of WRRF #A remain at a constant level between 37 and 49°C and decrease at temperatures around 52°C. Specific methane yields of WRRF #B increase from 34 to 40°C and remain almost constant at higher temperature levels, whereas values of WRRF #C are constant up to 40°C and show a maximum at 43°C. The average methane contents vary between 63.9% and 65.4% at WRRF #A, 62.9% and 63.6% at WRRF #B, and 65.0% and 66.2% at WRRF #C for all temperature levels, which are all within the expected range for anaerobic digestion of

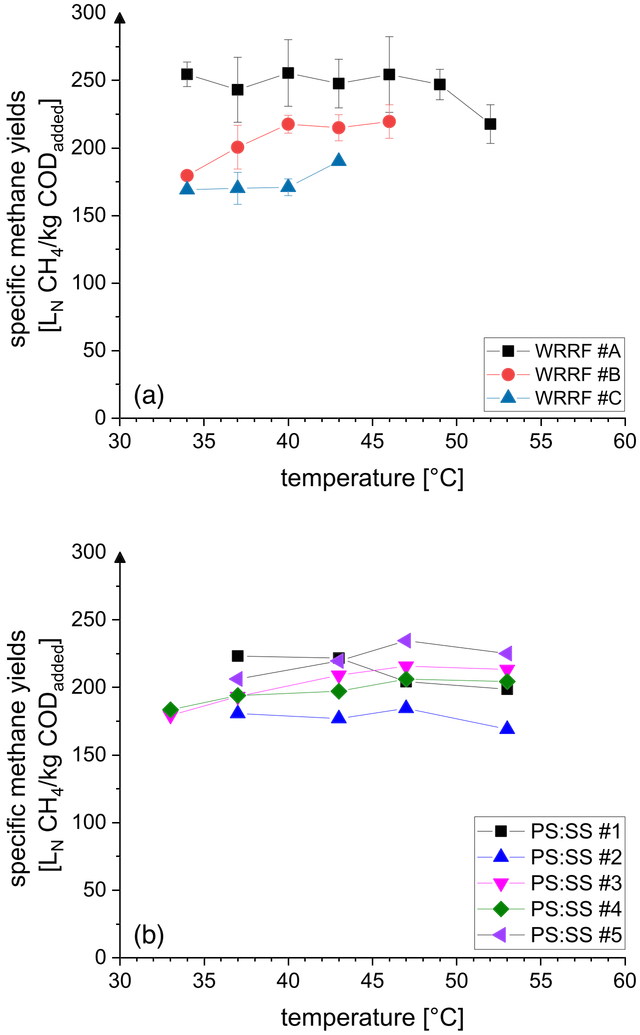

FIGURE 2 Specific methane yields based on COD balancing at temperature levels between 34 and 52°C for full-scale process data as averages (a) and between 33 and 53°C for process data from lab-scale digesters (each PS:SS mixture was simultaneously fed to digesters operated at each temperature level) (b).

raw sludge. A summary of the results for each temperature level is listed in Table 2.

COD elimination rate

COD elimination rates vary between 65.9% and 72.0% at WRRF #A, between 57.2% and 67.7% at WRRF #B, and between 64.9% and 70.2% at WRRF #C. For the lab-scale digesters, the COD elimination rates range between 60.6% and 64.2% for the PS:SS mixtures. OLRs vary between 1.5- and 2.2-kg COD/(m^3·day) for WRRF #A, around 1.5-kg COD/(m^3·day) for WRRF #B, and at a lower level of around 0.5 COD/(m^3·day) at WRRF #C. The range of OLRs in the lab-scale digesters is around 1.7-kg COD/(m^3·day) for the PS:SS mixtures.

Process stability and sludge stabilization

Besides slight changes in the previous results of specific methane yields and methane content, organic acid concentrations, VFA/TA, and BOD_5/COD ratios provide both additional insights into process stability and sludge stabilization at each temperature level. For all WRRFs, data of acetic acid equivalents are limited and were analyzed with different methods (WRRF #A with cell tests, WRRF #B with GC, and WRRF #C with Nordmann titration). However, concentrations of acetic acid equivalents are below 500 mg/L for each temperature level at all three WRRFs.

For the lab-scale digesters, the parameters VFA and the VFA/TA and BOD_5/COD ratios are listed in Table 3 for each temperature level. VFA concentrations of all PS:SS mixtures increase with the digester temperature and remain below 500 mg/L (titration) at all temperature levels, whereas concentrations of acetic and propionic acids are significantly below 100 mg/L (GC). For the PS:SS mixtures, TA slightly increases from 4310 to 5260 mg/L between 33 and 53°C. The VFA/TA ratios are below 0.1 at each temperature level. In addition, the BOD5/COD ratios of the PS:SS mixtures remain below 0.15.

Sludge liquor composition

In Figure 3, the concentrations of soluble COD and of the ammonium-nitrogen are shown for each PS:SS mixture. The soluble COD concentrations in the sludge liquor raises with increasing digester temperature (cf. Figure 3a). Concentrations at 33 and 37°C and at 43 and 47°C are on a similar scale, whereas concentrations at 53°C are 2.6 to 5.8 times higher at 53°C than those at 37°C. The ammonium-nitrogen concentrations slightly increase at higher digester temperatures (cf. Figure 3b). In comparison with 37°C, maximum values for the mixtures of PS:SS are reached at 53°C up to 1.3 times higher.

Sludge dewatering

Sludge dewatering process data from the WRRFs do not allow direct conclusion of dewatering results in regard to the digester temperature due to digester design, availability, or frequency of the process data. Therefore, the effect of the digester temperature on the sludge dewatering is presented for the biosolids of the lab-scale digesters.

The TVS content decreases with the digester temperature from 66.0% at 37°C to 63.9% at 53°C. Phosphate concentrations slightly increase from 28.1 mg/L at 37°C to

Temperature [°C]	VFA [mg/L]	VFA/TA [mg/L]	BOD_5/COD [-]
33	311 ± 19	0.07 ± 0.01	0.10
37	326 ± 33	0.07 ± 0.01	0.14
43	377 ± 10	0.07 ± 0.00	0.10
47	422 ± 46	0.08 ± 0.01	0.10
53	488 ± 35	0.09 ± 0.01	0.09

TABLE 3 Summary of VFA, VFA/TA, and BOD_5/COD ratios for each temperature level in the lab-scale digesters (mixture of PS:SS #4, averages of the VFA/TA ratios at three different days, and the BOD_5/COD ratios at 1 day).

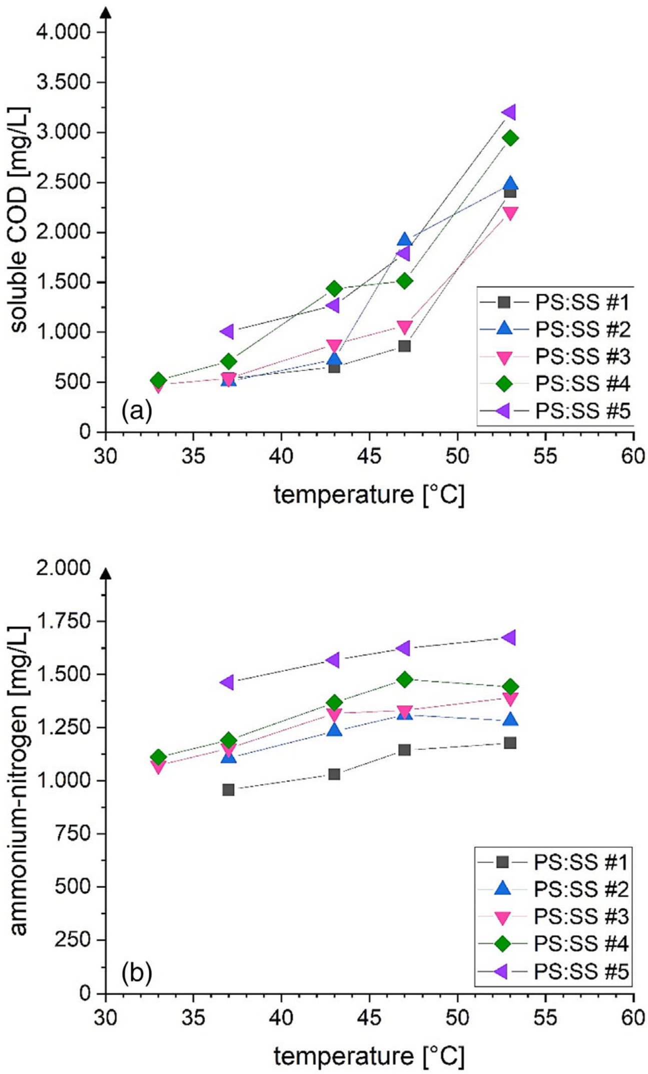

FIGURE 3 Correlation between digester temperature and soluble COD (a) and ammonium-nitrogen (b) in sludge liquor of the lab-scale digesters.

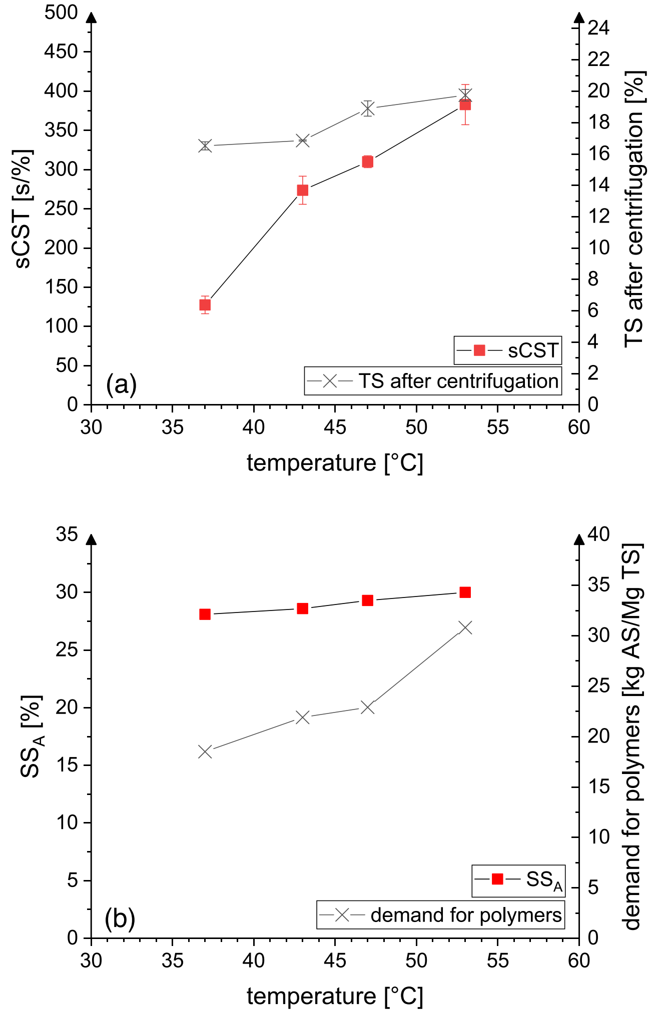

FIGURE 4 Correlations between digester temperature and sCST and TS after centrifugation (a) and SS_A and polymer demand (b) of biosolids of lab-scale digesters operated between 33 and 53°C.

30.5 mg/L at 53°C for PS:SS #5. Soluble protein concentrations increase with the digester temperature from 44 mg/L at 37°C to 140 mg/L at 53°C.

The results of the dewatering tests (sCST, TS after centrifugation, SS_A, and determination of the polymer demand) at different temperature levels are shown in Figure 4. The sCST results almost linearly increase with increasing digester temperature, reaching values up to 3 times higher values at 53°C compared with 37°C. The lowest sCST occurs at 37°C, whereas the highest values are obtained at 53°C (cf. Figure 4a). The results of TS after centrifugation slightly increase with the digester temperature from 16.5% at 37°C to 19.8% at 53°C (cf. Figure 4a).

Measurements of SS_A show a slight increase from 28.1% to 30% for sludge digested between 37 and 53°C (cf. Figure 4b). Similarly, the polymer demand results show almost a doubling from a minimum of 18.5-kg AS/Mg TS at 37°C to a maximum of 30.8-kg AS/Mg TS at 53°C.

DISCUSSION

Effect on biogas quantity and methane contents

Specific methane yields, methane contents and COD elimination rates for full- and lab-scale data regarding the specific substrate composition correspond with reported values in the literature (Astals et al., 2013; Huete et al., 2006; Tchobanoglous, 2014).

It should be noted that a wider range of OLR occurs in the full-scale digesters because of the site-specific design of the digesters. Although the digesters at WRRF #A and #B are arranged in series, the OLRs are calculated for the volume of the first digester as the gas production predominantly occurs in the first digester and the second digester operates as a storage tank without heating and mixing. Further, WRRF #A practices co-digestion and WRRF #B intermittently feeds external grease trap waste to their digesters. In contrast, the two digesters at WRRF #C are connected in parallel mode and do not practice co-digestion resulting in lower OLRs. However, the selection of constant temperature levels from full-scale process data correlates with the annual cycle of the lowest digester temperature in winter and the highest digester temperature in summer. Thus, full-scale process data must be interpreted considering the reduced periods available for data evaluation in winter and summer (cf. Table 2), seasonal effects, and inconstancy of process parameters (e.g., variation in raw water quantities, wastewater temperature, sludge age, and HRT).

The operation of the lab-scale digester minimizes these effects and emphasizes the constancy of specific methane yields, methane contents, and the COD elimination rate. However, the specific methane yields, methane contents, and COD elimination rates of the process data indicate a stable degradation process up to 2.2-kg COD/(m^3·day) in full-scale digesters and up to 1.7-kg COD/(m^3·day) for PS:SS mixtures at lab-scale digesters at all temperature levels.

Effect on process stability and sludge stabilization

Taking into consideration the findings of specific methane yields, methane contents, and COD elimination rates, the degradation process is considered stable at temperatures between 33 and 53°C. VFA concentrations of all PS:SS mixtures increase with digester temperature, which is consistent with previous results reported by Buhr and Andrews (1977), Pfeiffer (1990), and Buffière et al. (2013). Additionally, concentrations of acetic acid equivalents below 300 or 500 mg/L indicate a well-established anaerobic degradation process in full- and lab-scale digesters (fed with PS:SS mixtures) (DWA, 2014; WEF, 2018). Although, VFA concentrations slightly increase at higher temperature levels due to enhanced hydrolysis or slowed methanogenesis (Donoso-Bravo et al., 2009).

However, TA concentrations of PS:SS mixtures are slightly higher than values between 2500 and 5000 mg/L, which usually indicate well-established digesters (WEF, 2018). Higher TA concentrations at thermophilic compared with mesophilic temperature (de la Rubia et al., 2005; Kardos, 2011; Song et al., 2004) and with increasing digester temperature (Garber, 1954; Golueke, 1958) have been previously reported in the literature. Increased alkalinity in digesters with increasing digester temperature can be traced back to the degradation of nitrogenous organic compounds, sulfate reduction, the release of orthophosphate, and an increase in VFA (Song et al., 2004). Further, the VFA/TA ratios are below 0.1 at each temperature level for PS:SS mixtures indicating no overloading of the anaerobic degradation process (Zickefoose & Hayes, 1976). A slight increase in the VFA/TA ratio with increasing digester temperature has been previously reported in literature by Bouskova et al. (2006) and Wilson et al. (2008).

In addition, the BOD_5/COD ratios of PS:SS #4 remain below 0.15, demonstrating sufficient biosolids stabilization for all temperature levels (DWA, 2020). Considering the results of VFA, the VFA/TA and BOD_5/COD ratios, process stability, and sufficient sludge stabilization are demonstrated for this PS:SS mixture.

Effect on sludge liquor composition

Concentrations of soluble COD and ammonium-nitrogen in the sludge liquor indicate additional loads for biological wastewater treatment, as sludge liquor is returned to the influent of the WRRF or the biological treatment. Further, the ammonium concentration is also a relevant indicator of inhibition due to free ammonia dissolved in the liquid phase.

A significant increase in soluble COD concentrations can be partly attributed to the increase in soluble proteins and organic acids because of enhanced hydrolysis or slowed methanogenesis (Donoso-Bravo et al., 2009) and the destruction of the sludge flocs at higher digester temperatures (Bouskova et al., 2006). With increasing digester temperature, ammonium-nitrogen concentrations slightly increase because of enhanced degradation of proteins and a shift in the ammonia and ammonium equilibrium. Initial inhibition by ammonia can occur above 1700 mg/L (Chen et al., 2008). Ammonium-nitrogen concentrations for PS:SS mixtures are just below (PS:SS #1 to #4) or within (PS:SS #5) this value. Considering the specific methane yields, methane contents, and VFA concentrations, the anaerobic degradation process is considered stable at the temperature levels between 33 and 53°C.

However, it is expected that additional concentrations and load of soluble COD can be handled during the proceeding biological treatment of the sludge liquor. A significant formation of recalcitrant compounds, as known from thermal pressure hydrolysis of sludge pre-treatment at temperatures between 160 and 180°C, passing the subsequent aerobic treatment step, inhibiting the deammonification process or ending up in the effluent of the WRRF, are assumed to be negligible in the temperature range between 33 and 53°C (Balasundaram et al., 2022; Zhang et al., 2016).

Effect on sludge dewatering

Several aspects such as organic content, concentrations of soluble organic matter, phosphates, proteins, and the (digester) temperature can affect the sludge dewatering (DWA, 2019). Organic compounds impair dewaterability because of their lower density, higher compressibility, higher surface charge, and water binding capacity compared with inorganic compounds (DWA, 2019).

The increase in organic content, phosphates, and proteins dissolved in the sludge liquor can enhance the water binding due to altered charge ratios of exopolymeric compounds, which are critical for coagulation and flocculation properties, leading to a deterioration of sludge dewatering and an increase in the polymer demand at higher digester temperatures (Kopp, 2001). However, the decrease in TVS with the digester temperature for PS:SS mixtures indicates better dewaterability. In contrast, the concentrations of phosphates and soluble proteins only slightly increase with the digester temperature. The increase in the concentrations of soluble COD and soluble protein of the PS:SS #5 agrees with previously reported results by Bouskova et al. (2006) for digester temperatures at 33, 35, 37, 39, and 55°C.

The sCST is known as an indicator of the proportion of fine particles in the sludge and thus of the polymer demand, whereas the TS after centrifugation is less affected by the particle size distribution (DWA, 2019). In addition, thermogravimetric measurements of SS_A allow the prediction of the (full-scale) dewaterability result and the measurement with streaming potential measurements determines the polymer demand (DWA, 2019).

Overall, sCST results show a clear deterioration with increasing digester temperature, whereas TS after centrifugation slightly increases with the digester temperature indicating better dewaterability (cf. Figure 4). Bouskova et al. (2006) also observed divergent results with sCST and TS after vacuum filtration for 33, 35, 37, 39, and 55°C. The authors explain the different results by the increasing percentages of fine particles at higher digester temperatures, which worsens the filterability but not the compressibility. Both dewaterability tests (TS after centrifugation and SS_A) and the tests providing information on the polymer demand (sCST and the determination of the polymer demand with streaming potential measurements) show correlation coefficients of 0.96 and 0.81, indicating a very high degree of cohesion.

However, Rossol et al. (2005) compared the dewaterability and the polymer demand for biosolids digested at 37 and 42°C by determining the specific filter resistance and sludge pressing after polymer addition. Pressing results at 6 mg AS/g TS showed an increase in TS up to 33% when a digester was operated at 42°C. These tendencies from Rossol et al. (2005) can be confirmed with the presented polymer demand increasing by +18.4% when comparing digester temperature of 37 with 43°C. However, the increase in the polymer demand is dependent on the digester temperature as the release of total EPS from the floc and the denaturation of proteins occur above 40°C leading to a reduced ability to bind water (DWA, 2019). In addition to the digester temperature, further aspects such as digestion time, substrate quality fed to the digester, and floc structure (surface charge, particle size) play also a relevant role when considering the dewatering result and the polymer demand.

CONCLUSIONS

Using digesters as seasonal heat storage in temperate climates in the context of a holistic heat management at WRRFs requires the operation at different temperature levels within mesophilic and thermophilic temperature ranges. Following on from a previous publication by the authors on the energy assessment of the concept "digesters as heat storage," relevant data on process stability, sludge liquor quality, and dewaterability are considered to evaluate the operational aspects of operating digesters as heat storages.

Both process data and operational experiences from three WRRFs and additional process data from lab-scale experiments show comparable effects of the digester temperature between 33 and 53°C on the considered operational aspects. In total, the anaerobic degradation process within temperatures between 33 and 53°C is stable for HRT above 20 days and OLR up to 2.2-kg COD/(m^3·day). Nevertheless, an increase in soluble COD and the polymer demand is expected with increasing digester temperature.

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DATA AVAILABILITY STATEMENT

Research data are not shared.

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