Impacts of blackwater co-digestion upon biogas production in pilot-scale UASB and CSTR reactors

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Abstract
The performance of two pilot-scale blackwater co-digestion reactors was studied as an effort to reproduce the transition of current wastewater infrastructures to source-separated sanitation systems. The main focus of this study remained on assessing the feasibility of blackwater co-digestion via two different approaches: for either municipal wastewater in an upflow anaerobic sludge blanket reactor or mixed sewage sludge in a continuously stirred tank reactor. For the CSTR, increasing methane yields of 222 to 332 l CH_4 kg/$COD_{removed}$ were achieved by increasing the blackwater load in the influent from 0 to 35% (COD % in influent load). COD removal ranged from >70% to 78% between transition states of 0–25%, while at high transition states of approx. 35% blackwater 60% COD-removal were observed. For the UASB reactor, COD removals of 57–67% were reported despite high COD loading rates of 6.1–8.4 kg/(m^3 d). Removal of organic matter was successfully achieved in both cases; blackwater co-digestion alongside raw sludge proved better in terms of biogas generation within the CSTR reactor. Thus, current digestors in wastewater treatment plants can be integrated in new concepts for separate treatment of different household wastewater streams.

Keywords
Anaerobic treatment; biogas yield; COD-removal, source-separated sanitation systems; transition states.

INTRODUCTION
In view of the external pressures exerted on current wastewater facilities such as climate and demographic change and the scarcity of water, energy and nutrients, source-separated sanitation systems become more attractive as an alternative to existing infrastructures. Source-separation of wastewater streams into greywater and blackwater is appropriate in terms of furthering the use of domestic water and more efficient treatment with regards to nutrients and energy recovery.

Vacuum toilets for the collection of blackwater at low-dilution enable water savings through diminished consumption of flushing water, thus resulting in high concentrations of wastewater constituents and low volumes during treatment. Vacuum toilets represent a state-of-the-art technology complying with sanitary requirements. A water consumption of 0.5 to 1.5 litres per flush (Lange *et al.* 2000) brings about a highly concentrated blackwater stream which provides the opportunity of more efficient treatment with regards to energy. For instance, anaerobic treatment of blackwater for biogas production has proved technically feasible (Wendland 2008, Graaff 2010). Furthermore, the flushing water consumption can be decreased by around 80% (Lange *et al.* 2000), not to mention the technical advantages in operation, hygiene and energy balance. Due to low pressure within vacuum systems, exfiltration of wastewater through damaged pipes is impossible of occurring. Additional flushing to avoid clogging are not required due to high transport velocities of the air-water mixture within the vacuum lines (DWA 2005). Furthermore, shallow installation depths and lower construction costs of vacuum sewers are additional benefits of these systems.

In spite of the clear advantages, immediate implementation of centralised blackwater digestion is unrealistic, as existing wastewater infrastructures (characterised by their long service lives) should be exploited and best used during a step-by-step implementation of new sanitation technologies into current wastewater infrastructures. Therefore, transition states have to be considered, in which blackwater separation and digestion can be set up incrementally and the residual system must remain functional.

In Germany many WWTPs with a capacity >300 kg BOD_5/d have an anaerobic sewage sludge digestion stage which often has spare hydraulic reserves for the co-digestion of substrates (DWA 2009). Substrates characterised by high COD concentrations and solids content, e.g. primary and secondary sludge, are normally stabilised anaerobically within a CSTR; its design reduces the risk of clogging and allows easy operation. Moreover, in tropical climates worldwide with less strict regulations, effluents from WWTPs have been treated anaerobically in UASB reactors.

Within a UASB reactor, the HRT can be set independently of the SRT to a large extent, since microorganisms are capable of conglomerating to pellets. Therefore, upflow velocities must be high enough to lift the biomass but low enough to not wash it out. A HRT of 10 hours for high-strength domestic wastewater in a UASB digester has proved sufficient (Mahmoud 2008), while a long SRT can be assured due to biomass immobilization (Ratanatamskul and Siritiewsri 2015). At a mesophilic operation, relatively constant temperatures must be assured for maintaining a high conversion rate of organic compounds to biogas. A technical drawback of UASB reactors is the considerable methane loss through dissolved methane in reactor effluent due to high flow rates; this effect is more evident at low organic concentrations (Kroiss and Svardal 2015).

Within this study, two technical approaches for a step-by-step set-up of centralised blackwater digestion were considered: digestion in either a continuously stirred tank reactor (CSTR) or an upflow anaerobic sludge blanket (UASB) reactor. Blackwater from vacuum toilets was collected separately and treated anaerobically as co-substrate (to sewage sludge) in a CSTR reactor. In a second approach blackwater was mixed with municipal wastewater and digested in a UASB reactor. In both scenarios, the blackwater fraction in the reactor influent (% COD) was incrementally increased in order to simulate different states during transition to source-separated systems. The key objective of this study was to assess the technical viability of the anaerobic co-treatment of blackwater in CSTR and UASB reactors at increasing transition states (0–35% blackwater in terms of COD load in the reactor influent), hereby investigating operation stability, methane yield and COD elimination. Additionally, both systems were compared with regard to operational parameters as well as removal efficiencies. To the best of the authors' knowledge no one other than the authors of the study has thus far considered blackwater co-digestion with primary and excess sludge or municipal wastewater in CSTR or UASB reactors respectively.

MATERIAL AND METHODS

Substrates

Blackwater from vacuum toilets was obtained from the facilities within the Institute for Sanitary Engineering, Water Quality and Solid Waste Management at the University of Stuttgart (cf. Table 1), while at higher transition states the UASB reactor was provided with blackwater from the local railway company for load completion. Municipal wastewater, mixed sewage sludge and digested sludge (CSTR inoculum) were collected from the Treatment Plant for Education and

Research (LFKW) at the University of Stuttgart, which has a capacity of approx. 8,500 population equivalents (PE) – the mean value for 2015 based upon 120 g COD/(PE·d).

Municipal wastewater was collected daily between 11 am and 1 pm, as this time window corresponded to COD concentration peaks at the inlet. The wastewater was stored in a tank at 15 °C. The UASB reactor was inoculated with mesophilic pellet sludge from a paper mill.

Characterization of blackwater was carried out during this work, as not many characteristic values for blackwater from vacuum toilets are available in the literature (cf. Table 1). Influent quality of all the substrates was characterised by significant fluctuations (cf. Table 1 and 2). Blackwater from the local railway company proved more dilute than blackwater from the LFKW and showed more urine in its composition, as it can be inferred for instance by comparing corresponding pH values. Transition states of 0 to 35% blackwater (regarding COD % in influent load) were investigated.

Table 1. Chemical characterisation of blackwater from vacuum toilets (6 toilets, approx. 20 toilet users per day) of the LFKW at the University of Stuttgart.

Parameter	Unit	Mean value	Standard deviation	Median value	Min-max	Number of values (n)
pH	-	7.3	± 0.4	7.2	6.7 – 8.6	33
COD	mg/l	11,556	± 4,717	10,700	3,350 – 25,800	86
$COD_{soluble}$	mg/l	2,995	± 998	3,050	1,090 – 5,380	51
BOD_5	mg/l	5,772	± 1,601	5,989	3,750 – 7,424	5
TS	g/kg	8.6	± 3.2	8.1	4.1 - 20	77
VS	% TS	72.1	± 7.4	74.0	46.9 – 84.3	77

Table 2. Chemical characterisation of blackwater from vacuum toilets (6 toilets, approx. 20 toilet users per day) of the LFKW at the University of Stuttgart.

Wastewater stream	TS	VS	COD	$COD_{soluble}$	TSS	pH
	g/kg	%TS	g/l	g/l	mg/l	-
Mixed sludge	25.3±7 (n=28)	83.4±3.5 (n=28)	35.7±7 (n=28)	-	-	-
Municipal wastewater admixed with blackwater	-	-	3.5±3.2 (n=121)	0.22±0.16 (n=52)	2348±2632	-
Blackwater from the local railway company	4.0-10.0 (n=8)	37.7-68.2 (n=8)	2.9–12.6 (n=9)	-	-	7.2–8.2 (n=7)

Set-up

Two pilot-scale anaerobic reactors (constructed by the company HST Systemtechnik GmbH & Co. KG) with effective volumes of 630 L (CSTR) and 720 L (UASB) made of stainless steel were used for the blackwater co-digestion (cf. Figure 1). A mesophilic operation (34 °C) was pursued for both reactors and the HRT_{CSTR} was set to 21 d. The CSTR (start-up time: 75 d) was operated with a mixture of primary and secondary sludge at a ratio 3:1 (v/v) as well as increasing amounts of blackwater from the LFKW over different experimental phases which lasted on average 2 HRT_{CSTR}. The sludge was recirculated in the digester by an external progressive cavity pump to avoid layers forming and ensure mixing of substrate and bacteria. Primary sludge, secondary sludge and blackwater were admixed using a grinder pump, thus macerating toilet paper and other gross solids to a small particle size. The mixture was kept in a storage tank at 15°C under permanent mixing. The CSTR was fed every hour semi-continuously with substrate from the storage tank. The effluent was removed via a syphon pipe to avoid biogas losses and collected for further analysis. Biogas was collected in the upper part of the reactor and measured by drum-type gas meters from Ritter (TG 05), while biogas composition was analysed every second day by gas chromatography.

In case of the UASB reactor, the design was modified to a simpler reactor set-up without an internal phase separator to avoid clogging. The UASB experimental phases lasted 2 HRT_{CSTR} as well. Biogas collection was again in the upper part of the reactor, while the effluent was stored in a separate tank with a HRT of 1 h to degas methane from the reactor effluent. The biogas produced was metered by drum-type gas meters from Ritter and analysed daily. For the UASB reactor (inoculated with paper mill sludge; start-up period: 73 d), municipal wastewater was collected from the LFKW, admixed with black water, heated to 35 °C and pumped by a progressive cavity pump into the reactor.

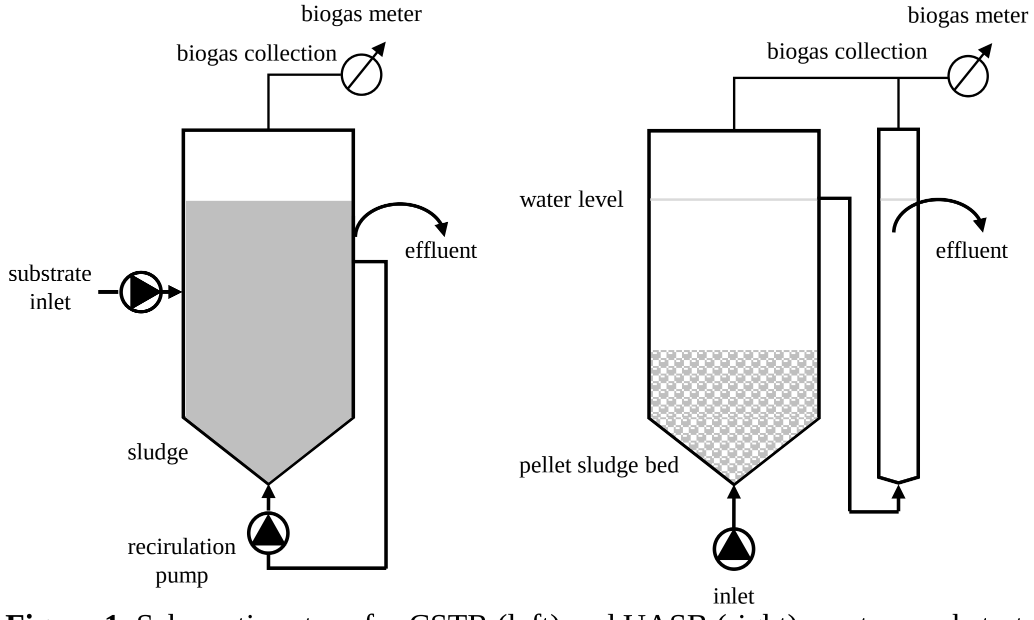

Figure 1. Schematic set-up for CSTR (left) and UASB (right) reactors; substrate storage tanks are not depicted.

Analytics

COD (chemical oxygen demand) was determined according to DIN 38409 (1980). Dissolved COD was measured after filtering the samples with aid of nylon membrane filters with a pore size of 0.45 µm.

Total solids (TS) were determined according to DIN 38409 (1987).

Biogas samples were collected as triplicates in a 0.5 mL gas tight glass syringes and injected in a Gas Chromatograph (Perkin Elmer Auto System Gas Chromatograph) equipped with a flame ionization detector and a capillary column (Agilent Technology, USA). CH_4 and CO_2 contents were analysed using nitrogen as carrier gas. Using a calibration line, the results were calculated by linear regression. The gas produced from the experiments has been normalized to standard temperatures and pressure conditions as given in VDI 4630 (2006).

Procedure

The COD loading rates to the CSTR are given in Table 3, while in Table 4 the COD loading rates to the UASB reactor are listed.

Table 3: COD loading rates to the CSTR (average ± standard deviation (number of values))

Transition state	$[COD_{BW}/COD_{tot}$ * 100 %] at the reactor inlet	0	1,8 ± 0,6 (12)	2,8 ± 0,6 (3)	18,3 ± 3,8 (7)	24,6 ± 6,7 (10)	33,8 ± 4,0 (9)
CSTR	[kg COD/(m³d)]	0,93 ± 0,5 (21)	1,6 ± 0,4 (17)	1,7 ± 0,3 (6)	1,2 ± 0,3 (13)	1,1 ± 0,2 (10)	0,9 ± 0,2 (11)

Table 4: COD loading rates to the UASB reactor (average ± standard deviation (number of values))

Transition state	$[COD_{BW}/COD_{tot}$ * 100 %] at the reactor inlet	0	1,9 ± 1,6 (20)	3,9 ± 3,5 (26)	4,2 ± 3,4 (28)	14,0 ± 17,2 (28)
UASB	[kg COD/(m³d)]	6,8 ± 2,5 (5)	6,1 ± 3,4 (17)	8,4 ± 6,2 (27)	7,8 ± 6,2 (28)	7,7 ± 7,4 (28)

RESULTS AND DISCUSSION

General aspects

The temperature level and pH were reported to be stable for mesophilic operation in both reactor types over the course of the pilot-scale experiments (with only sporadic fluctuations in the UASB reactor due to varying pump performances and occasional clogs of the inlet systems). The HRT was kept stable in both reactors, while the COD loading rates were varied deliberately in accordance with changes in influent composition.

Biogas quality, COD removal and COD loading rate

For the CSTR configuration proposed, loading rates of 1.6 and 0.9 kg COD $m^{-3}\,d^{-1}$ 1.0 and 0.5 kg VS $m^{-3}\,d^{-1}$ were achieved at 1.8 and 33.8 % COD_{BW}/COD_{tot} in the influent respectively. The decreasing organic loading rates were ascribed to substrate dilution due to an increasing blackwater fraction at the inlet over the course of transition to source-separated systems. Furthermore, a stable methane concentration of around 60 % (v/v) was reported over the course of the investigated transition (cf. Figure 2). The process was not adversely affected by blackwater addition, whereas a slight increase in the methane concentration could be observed with higher blackwater fractions. In the literature, methane concentrations in biogas of 55–75 % are typical for sewage sludge-based digestion (ATV-DVWK 2003b). In addition Wendland (2008) reported 60 % methane in biogas for the anaerobic treatment of blackwater in a lab-scale CSTR reactor (V=1L). COD removals of 60–78 % achieved within this study were higher than the reference value reported by ATV-DVWK 2003a for mesophilic operation of sewage sludge digestion (55 % COD removal). Up to a 25 % transition state elimination rates >70 % COD could be reached, while this value dropped to 60±9 % at 33.8 % COD_{BW}/COD_{tot} in the influent. The decrease was attributed to an adaptation time of 2 HRT within the last experimental phase along with a relatively high increase in the blackwater fraction at the reactor inlet (cf. Table 3); in the literature a minimum adaption time of 3 HRT is recommended (VDI 4630 2006). However, this result is in accordance to (Wendland 2008), who reported 62 % COD elimination within a blackwater-based digestion.

For the UASB reactor, loading rates from 6.1 to 8.4 kg COD/(m³ d) were achieved at 1.9 to 14.0 % COD_{BW}/COD_{tot} in the influent. The variation of the loading rates was not linked with the increasing blackwater fraction at the inlet, but rather with varying COD concentrations of the municipal wastewater. Furthermore, an increasing biogas quality from 60–71 % (v/v) and COD removal efficiencies from 57-67 % were reported over the course of the transition to source-separated systems. According to Seghezzo *et al.* (1998), who reviewed several cases of anaerobic sewage treatment, removal efficiencies between 51-63 % were observed. The COD removal efficiency of the UASB reactor used in this study was higher, which was ascribed to higher blackwater fractions. Graaff *et al.* (2010) reported a methane concentration of 78 % for a blackwater-based digestion in the UASB reactor, which was taken as reference for a transition state of 100 %. The increasing biogas quality of the UASB reactor indicates that the reference was achieved with increasing fractions of blackwater at the inlet. Moreover, the COD loading rate was observed within the proposed ranges of <25 kg COD/(m³d) by Lettinga (1995).

Due to a technical malfunction during the last investigated transition state biogas quality decreased. This was attributed to higher loading stress upon the anaerobic bacteria. The malfunction was triggered by the accumulation of suspended solids at the UASB inlet. It was supposed that the solids did pass the pellet sludge bed but then accumulated in the upper part of the reactor, affecting its hydraulic performance and methane degassing. Similar problems were reported by Lohani *et al.* (2015), who observed a COD accumulation of 25 % (in terms of COD in the influent) and a COD conversion of 33 % to methane.

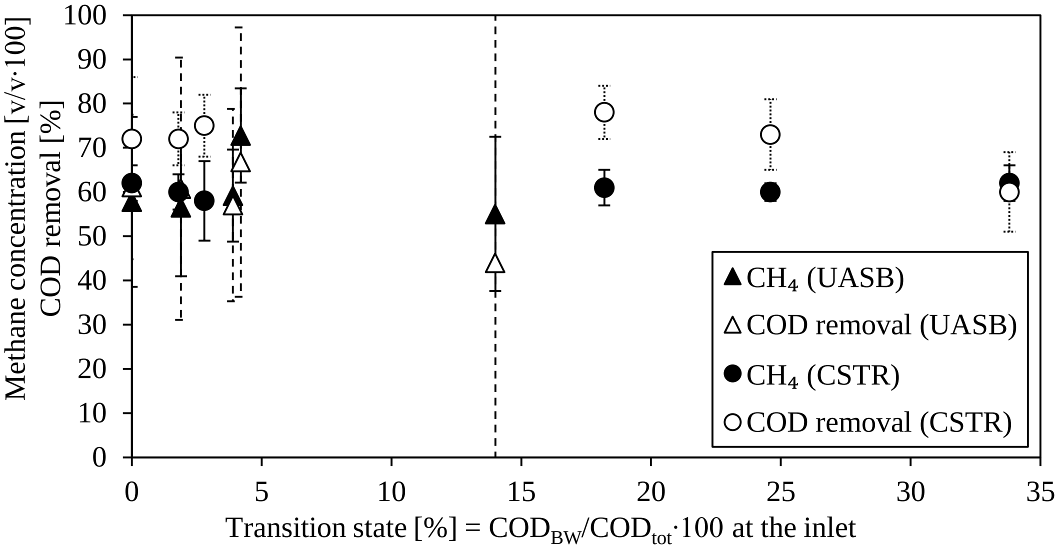

Figure 2. Methane concentration in biogas and COD elimination during different transition states for CSTR (solid and empty circles) and UASB (solid and empty triangles) reactors. Bars indicate standard deviation of methane fraction, while dotted lines indicate standard deviation of COD elimination.

Methane yield and methane production rate

While operation with sewage sludge only (start-up phase) in the CSTR resulted in a methane yield of 222 L CH_4/kg $COD_{removed}$ – reference values: 190–330 L CH_4/kg $COD_{removed}$ (DWA 2015), assuming 65 % CH_4 (v/v) in the biogas, a COD:VS ratio of 1.7 (DWA 2014) and 55 % COD removal – the increase of % blackwater in the influent was associated with an increase in methane yield from 222 to 332 L CH_4/kg $COD_{removed}$ (cf. Figure 3). This was attributed to lower organic loading rates at higher COD_{BW}/COD_{tot} ratios at the inlet as well as better anaerobic degradability of blackwater in comparison to raw sludge. Blackwater generated within the institute's facilities was analysed and a $COD_{dissolved}/COD_{tot}$ ratio of 0.27 ± 0.10 (n=51; cf. Table 1) was obtained, which indicates that almost 1/3 of the COD contained in blackwater is soluble, so more readily biodegradable matter is available to the anaerobic microorganisms. Specific methane generation amounted to 379 and 207 L $CH_4/(m^3\ d)$ at 1.8 and 33.8 COD_{BW}/COD_{tot} in the influent respectively.

As mentioned earlier, the majority of the COD load accumulated within the UASB reactor and was not properly digested. The accumulation effect resulted in a low methane yield of 27 to 77 L CH_4/kg $COD_{removed}$; additionally, comparably low COD conversion rates to biogas were observed. Due to the UASB's modified design, it was not possible to determine the starting point of the accumulation of the suspended solids. However, the permanent gap between COD load and COD in the effluent and the low methane yield indicates that the accumulation process began at an early stage. This problem should not be ascribed to UASB reactors in general, but to the modified design utilised within this study. Nevertheless, good COD removals rates were reported over all transition states investigated.

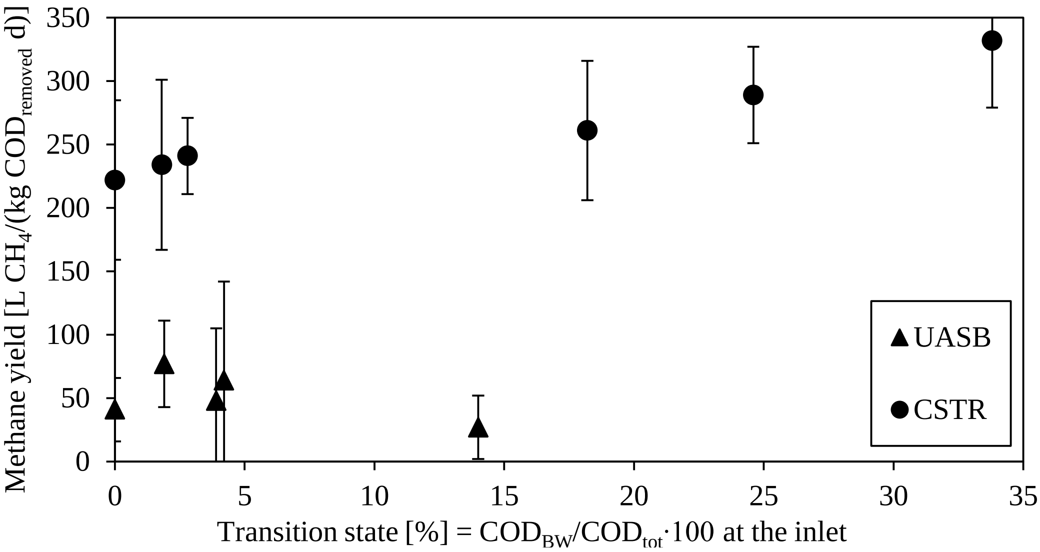

Figure 3: Methane yield during different transition states of CSTR (solid and empty circles) and UASB (solid and empty triangles) reactors.

The methane production rate compares the daily methane production when normalised against the volume of the studied CSTR and UASB reactors. The methane production rate (Figure 3) within the CSTR decreased slightly with increasing blackwater fractions. For the UASB no statements can be made due to high standard deviation and the technical malfunction. Although the following results are not representative, the methane production rate of the modified UASB reactor underperformed; treating municipal wastewater in the UASB yielded an average methane production rate of 140 L $CH_4/(m^3\ d)$, which increased to 184 L $CH_4/(m^3\ d)$ with increasing blackwater fractions.

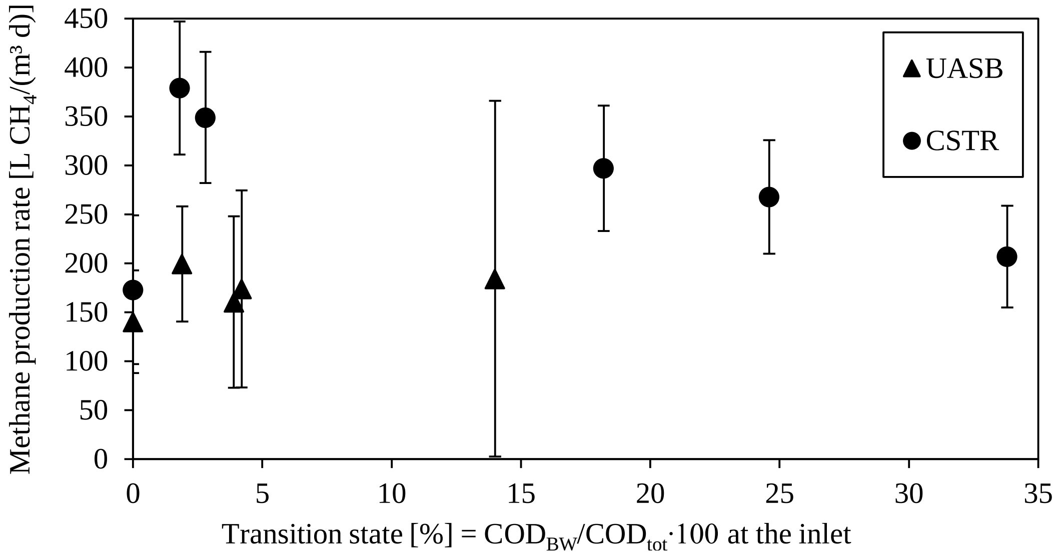

Figure 4. Methane production rate during different transition states for CSTR (solid and empty circles) and UASB (solid and empty triangles) reactors.

CONCLUSIONS AND OUTLOOK

- Transition states for blackwater co-digestion can be achieved in two alternative solutions: integration of anaerobic blackwater treatment into existing CSTR tanks for sewage sludge digestion or combined wastewater and blackwater treatment within a UASB reactor, However, application of UASB reactors would incur high investment costs, whereas existing digestors at larger WWTPs are often hydraulically underloaded, thus having spare capacity for the co-digestion of substrates.
- Removal of organic matter was successfully carried out in both cases. For the CSTR, COD removal ranged from approx. 70–78 % up to 25 % transition, while at a high transition state of approx. 35 % blackwater (%COD) in the influent 60 % COD removal were reported. Within the UASB reactor, COD removals of 57–67 % were achieved previous to the process failure.
- Co-digestion of blackwater with raw sludge proved better in terms of biogas generation within the CSTR reactor; increasing methane yields of 222 to 332 l CH_4 kg/$COD_{removed}$ were reported at blackwater load fractions in the influent (% COD) of 0 to 35 % respectively. For the UASB no statements with regards to methane yield could be made.
- Despite fluctuations in the substrate composition a stable operation of the CSTR was reported, which was supported by relatively constant methane concentrations in biogas of approx. 60 % as well as COD removal efficiencies >60 % over the entire CSTR operation.
- The incremental blackwater displacement to the anaerobic stage favoured biogas production due to enhanced methane yield and may contribute to better energy utilization in WWTPs, while current infrastructures are likely to remain functional. Nevertheless, impacts upon current WWTPs have to be considered and alterations to existing infrastructures will require individual planning.

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