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Impacts of blackwater co-digestion on biogas production in the municipal wastewater treatment sector using pilot-scale UASB and CSTR reactors

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ABSTRACT

The performance of two pilot-scale anaerobic reactors for blackwater co-digestion was studied as an attempt to investigate the transition of current wastewater infrastructures to source-separated sanitation. The focus of this study was to assess the feasibility of blackwater co-digestion at conventional wastewater treatment plants. Two scenarios were investigated; in scenario one, blackwater was co-digested with municipal sewage sludge in a 630 L continuous stirred-tank reactor (CSTR). In scenario two, blackwater was digested alongside high-strength municipal wastewater (concentration peak) in a 720 L upflow anaerobic sludge blanket (UASB) reactor. For CSTR operation, increasing methane yields from 222 to 332 L CH_4 kg/$COD_{removed}$ were achieved by enhancing the blackwater fraction at the reactor inlet from 0% to 35% (% total influent load as COD_{BW}/COD_{tot}). The observed COD removal ranged from 60% to 78% at 0.9–1.6 kg COD/(m³·d). For UASB operation, COD removals of 57%–67% were reported at COD loading rates of 6.1–8.4 kg/(m³ d). Removal of organic matter was successfully carried out in both reactors, yet blackwater co-digestion alongside raw sludge (CSTR) proved to be more advantageous to the plant in terms of overall biogas production. The results also indicate that municipal digesters can be successfully integrated in transition strategies for resource-oriented sanitation, thus potentially increasing energy utilization in the plant.

Keywords: Anaerobic treatment; Biogas yield; COD removal, Source-separated sanitation systems; Transition states

1. Introduction

In view of external pressures exerted on current wastewater facilities, for example, climate change, demographic growth as well as scarcity of water, energy and nutrients, source-separated sanitation systems have become more attractive as a supplementary alternative to conventional wastewater treatment processes. Indeed, separation of domestic wastewater into greywater and blackwater has proved to be appropriate in terms of furthering the use of domestic sewage as a resource, as it enables a more efficient treatment for the recovery of nutrients and energy [1–3].

With the use of low-flush vacuum toilets for blackwater collection, significant water savings can be achieved, resulting in high concentrations of wastewater constituents and low volumes for treatment [4]. In addition, vacuum toilets are a state-of-the-art technology and comply with hygienic and sanitary requirements. Due to operation at low pressure, exfiltration

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of wastewater is impossible to occur, for example, through damaged pipes. Shallow installation depths and lower construction costs are further advantages [5]. A renewed trend of larger implementations in pilot areas with source-separation systems has been gaining traction in Northern Europe [6].

Within existing infrastructures, implementation of vacuum systems for blackwater collection and transport has to be conducted step-by-step for economic and logistical reasons. In fact, existing wastewater infrastructures (characterised by their long service lives) are functioning systems that must be considered during the transition to source-separated sanitation. Therefore, at municipal wastewater treatment plants (WWTPs) transition states will arise, during which an incremental setup of blackwater co-digestion plays an important role. Thereby the residual system must remain functional. In order to use the energy content of blackwater for biogas production at low transition states, that is, only a small fraction of the inhabitants in a definite catchment area would have access to source-separated sanitation, blackwater needs to be added to a supplementary substrate source for anaerobic treatment, for example, municipal sewage sludge or high-strength municipal wastewater (concentration peak).

In Germany, many WWTPs with a capacity >600 kg BOD_5/d have municipal digesters for anaerobic sewage sludge stabilisation which are often operated at a hydraulic retention time (HRT) > 25 d, although 20 days are sufficient for mesophilic digestion [7], which implies that spare hydraulic reserves for co-digestion of substrates are available. Substrates characterised by high chemical oxygen demand (COD) and solid content as well as relatively low volume flows, for example, primary sludge (PS) and excess sludge (ES), are often stabilised anaerobically in municipal digesters (operated as CSTRs); its design reduces the risk of clogging and allows easy operation.

The treatment of municipal wastewater in full-scale UASB plants is a consolidated technology in warm-climate regions, mainly because of the lower activity of anaerobic microorganisms below 20°C wastewater temperatures [8]. Indeed, several UASB reactors in full scale are installed and operated worldwide to treat domestic wastewater, especially in Brazil, Colombia and India [8,9].

Within a UASB reactor, the HRT can be set independently of the sludge retention time (SRT), since microorganisms are capable of conglomerating to pellets, which are spherical granules of 1–3 mm size [10]. Therefore, upflow velocities must be high enough to lift the biomass but low enough to not wash it out, amounting to 0.5 to 0.7 m/h (average flow) for UASB reactors treating domestic wastewater [8]. For pellet sludge, a HRT of 10 h in a UASB digester has proved to be sufficient for the treatment of high-strength domestic wastewater [10], while enabling a long SRT due to biomass immobilization [11]. During mesophilic operation, the temperature must be kept relatively constant for the maintenance of high conversion rates of organic compounds to biogas. A technical drawback of UASB reactors is the considerable methane loss through dissolved methane in the reactor effluent due to high volume flow rates, which is more evident at low organic concentrations [12].

Table 1 shows a compilation of literature data for (1) blackwater digestion, (2) digestion of municipal sewage sludge and (3) digestion of municipal wastewater. For transition states as addressed in this study, there are no data available in the scientific literature.

Within this study, two scenarios have been investigated for WWTPs undergoing transition to source-separated sanitation. Focus was given to the incremental setup of blackwater co-digestion at centralised WWTPs. The first scenario considered blackwater co-digestion in municipal digesters alongside municipal sewage sludge [13] by operating a 630 L continuous stirred-tank reactor (CSTR). The second scenario contemplated the implementation of a UASB reactor to treat blackwater with high-strength municipal wastewater. Blackwater from vacuum toilets was collected separately and treated anaerobically as a co-substrate. In both scenarios (CSTR and UASB), the blackwater fraction in the reactor influent (% COD_{BW}/COD_{tot}) was used as indicator for transition, as it refers to the inhabitants' fraction that have access to source-separated sanitation. The ratio COD_{BW}/COD_{tot} was incrementally increased at the reactor inlet to simulate different transition states to source-separated sanitation. The key objective of this study was thus to assess the technical viability of blackwater co-digestion in the municipal wastewater treatment sector in a CSTR (scenario one) and a UASB reactor (scenario two) at increasing transition states (0%–35% COD_{BW}/COD_{tot} in terms of COD load in the reactor influent). Additionally, both systems were investigated with regard to operation stability, biogas production, operating parameters as well as removal efficiencies.

2. Materials and methods

2.1. Substrates

Blackwater from vacuum toilets was collected from the facilities of the Institute for Sanitary Engineering, Water Quality and Solid Waste Management at the University of Stuttgart (Table 2) and utilised as substrate for both reactors. The UASB reactor was also fed with blackwater from the local railway company for load completion. High-strength 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 treated, in 2015, the wastewater of approximately 8,500 population equivalents (PE), based on 120 g COD/(PE·d).

High-strength municipal wastewater used for the UASB feedstock was collected daily between 11 am and 1 pm, as this time span corresponds to COD daily concentration peaks. The collected wastewater was stored in a tank at 15°C. The UASB reactor was inoculated with mesophilic pellet sludge from a paper mill.

Table 2 shows the composition of blackwater (vacuum toilets) for relevant parameters. It can be inferred that blackwater is potentially suitable as a substrate for anaerobic digestion. First, the pH of 7.3 lays well within the optimum range of 6.5–7.5 for methanogenic activity [14], while high COD concentrations of >10 g/L are given, which favours anaerobic digestion. Additionally, a C:N:P ratio of 85:7:1 in blackwater indicates that nitrogen and phosphorus are sufficiently available for anaerobic microorganisms. Minimum nutrient requirements for the anaerobic process, expressed as C:N:P, are about 350–800:5:1 [15]. Furthermore, under consideration of a pH of 7.3, ammonium–nitrogen concentrations suggest that ammonia inhibition is not likely to take place during digestion [16].

Table 1
Literature data for the digestion of blackwater, municipal sewage sludge and municipal wastewater

	Unit	Substrates			
		Blackwater from vacuum toilets		Municipal sewage sludge	Municipal wastewater
	Reactor type	CSTR [3]	UASB [2]	CSTR [17–19]	UASB
OLR	kg COD/(m^3·d)	0.45	1.0	2.8–5[a]	2.5–3.5 [8] 1.2 kg BOD_5/(m^3·d) [20]
	kg VSS/(m^3·d)	–	–	1.7–3	–
HRT	–	20 d	8.7 d	>20 d	4 h [21] 8 h [20]
T	°C	37°C	25°C	Mesophilic	20–28 [8]
COD_{in}	g/L	8.1 ± 3.0	9.8–7.7	~40 g/L (estimated)	0.4–0.7 [21] 0.4– 0.5 [20]
Removal efficiency	% COD	62	78	–	68–85 [21], 46–60 [20], 55–75 (% BOD) [8]
	% VSS	57	–	PS: 60 ES: 38 PS + ES: 60	–
Methane yield	L CH_4/kg VSS_{in}	–	–	180–310	–
	m^3 CH_4/m^3 BW		1.8		
	L CH_4/kg $COD_{removed}$	342	–	190–330[a]	
Methane production	L CH_4 /(m^3·d)	94[a]	156[a]	575[a]	–
Methane concentration	Volume % in biogas	75	78%	60–70	70–80 [8]

[a]Calculated values.

Table 2
Chemical characterisation of blackwater from low-flush vacuum toilets (6 toilets, approximately 20 toilet users per day) of the LFKW at the University of Stuttgart

Parameter	Mean value	Standard deviation	Median value	Minimum–maximum	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
NH_4–N, mg/L	728	±131	734	305–1070	75
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
C:N:P, wt%	85:7.0:1	–	83:6.8:1	–	35

Influent qualities of several substrates utilised as CSTR and UASB feedstock are given in Table 3. Significant fluctuations were observed. Blackwater from the local railway company was more dilute than LFKW blackwater, while showing higher amounts of hydrolysed urine (this can be verified by the respective pH value). Transition states of 0%–35% blackwater (COD_{BW}/COD_{tot} as % in the influent load) were investigated. For instance, at 10% transition (COD_{BW}/COD_{tot} = 10%), it is assumed that the blackwater of 10% of the population discharging to the WWTP can be collected separately (and hence treated more specifically/efficiently). Therefore, the use of COD_{BW}/COD_{tot} as an indicator for transition enables an evaluation/comparison of both CSTR and UASB techniques in terms of overall energy gain for the plant.

2.2. Setup

Two pilot-scale anaerobic reactors made of stainless steel (constructed by the company HST Systemtechnik GmbH & Co. KG), with effective volumes of 630 L (CSTR) and 720 L (UASB), were operated for blackwater co-digestion (Fig. 1). A mesophilic operation (34°C) was pursued for both reactors and the HRT_{CSTR} was set to 21 d.

Table 3
Chemical characterisation of further influent substrates for the CSTR and UASB feedstock

Wastewater stream	TS, g/kg	VS, %TS	COD, g/L	$COD_{soluble,}$ g/L	TSS, g/L	pH
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)	2.35 ± 2.6 (*n* = 3)	–
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)

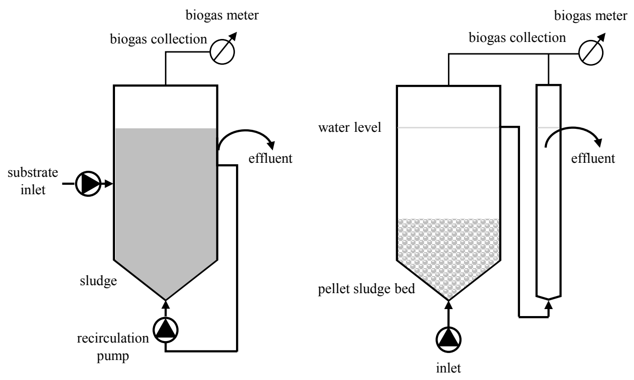

Fig. 1. Schematic setup for CSTR (left) and UASB (right) reactor; substrate storage tanks are not depicted.

The CSTR (start-up time: 75 d) was fed with a mixture of PS and ES at a ratio 3 PS:1 ES (v/v) as well as increasing fractions of blackwater from the LFKW over different experimental phases which lasted each approximately 2 HRT_{CSTR}. The sludge was recirculated in the digester by an external progressive cavity pump to avoid stratification and ensure an appropriate mixing of substrate and bacteria. PS, ES and blackwater were admixed using a grinder pump, which was capable of macerating toilet paper and other gross solids to a smaller particle size. The mixture was kept in a storage tank at 15°C under permanent mixing. The CSTR was fed semi-continuously every hour with substrate from the storage tank. The effluent was removed through 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 (Ritter, TG 05), while the methane concentration in the biogas was analysed every second day by gas chromatography.

With regard to the UASB, the design was modified to a simpler reactor setup without an internal phase separator. The experimental phases lasted two HRT_{CSTR} as well to allow biomass adaptation. Biogas was collected in the upper part of the reactor, while the effluent was stored in a separate tank (HRT ~1 h) to degas methane from the reactor effluent. The biogas produced was metered by a drum-type gas meter from Ritter and analysed daily. The UASB reactor was inoculated with paper mill sludge under a start-up time of 73 d. High-strength municipal wastewater was collected from the LFKW, mixed with blackwater, heated up to 35°C and pumped by a progressive cavity pump into the UASB reactor.

2.3. Analytics

The vast majority of the analysed parameters were determined according to the German Institute for Standardisation (DIN).

COD was determined according to DIN 38409 H 41 [22]. 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 H 1 [23].

Biogas samples were collected as triplicates in a 0.5 mL gas tight glass syringes and injected in a gas chromatograph (PerkinElmer; Autosystem gas chromatograph, T = 140°C, retention time = 3 min) equipped with a flame ionization detector and a capillary column (Agilent Technology, USA). CH_4 contents in biogas were analysed using nitrogen gas as carrier gas. Using a calibration line, the results were calculated by linear regression. The gas produced was normalised to standard temperatures and pressure conditions as given in VDI 4630 [24].

2.4. Procedure

The COD loading rates to the CSTR are given in Table 4, while Table 5 lists COD loading rates to the UASB reactor.

3. Results and discussion

3.1. General aspects

In both CSTR and UASB reactor types, the temperature level and pH proved to be stable for mesophilic operation during the pilot-scale investigations; however, fluctuations were observed during UASB operation due to varying pump performances and occasional clogs of the inlet systems. The HRT was kept constant in both reactors, while the COD loading rates varied in accordance with the influent composition. Table 1 allows a comparison of the results obtained in this study with literature data.

3.2. COD loading rate, COD removal efficiencies, effluent concentrations

For CSTR operation, loading rates of 1.6 and 0.9 kg COD/(m^3·d) or correspondingly 1.0 and 0.5 kg VS/(m^3·d) 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 higher blackwater

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

Transition state	% COD_{BW}/ COD_{tot} 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/ (m^3·d)	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 5
COD loading rates to the UASB reactor (average ± standard deviation (number of values))

Transition state	% COD_{BW}/COD_{tot} 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/(m^3·d)	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)

fraction at the reactor inlet, which is less concentrated than mixed sludge (Tables 1 and 2).

COD_{in} during phases 1–5 amounted to 35.1 ± 9.6 g/L. COD removals reached from 60% (phase 5) to 78% (phase 3) at organic loading rates of 1.6–0.9 kg COD/(m^3·d), which resulted in effluent values of 10.8 ± 4.10 g COD/L. The results are considerably higher than typical values for the digestion of sewage sludge (according to Seghezzo et al. [25] removal efficiencies between 51% and –63% COD are typical). Up to 25% transition, elimination rates >70% COD were reached, which was ascribed to the favourable relation PS/ES used and potentially to benefits inherent to co-digestion [26], for example, synergistic effects of microorganisms. At 33.8% COD_{BW}/COD_{tot} in the influent, the COD elimination dropped, however, to 60% ± 9%. This was probably associated with a higher substrate dilution, but can be potentially reverted by providing the bacteria with higher adaptation times. This last result aligns, however, with a COD elimination of 62% found for blackwater digestion [3] even at higher loading rates (Table 1). Correspondingly, TS_{in} during phases 1–5 was 24.4 ± 7.2 g/L; elimination of total solids reached in average 56%, so TS effluent values amounted to 10.7 ± 3.5 g/L.

For UASB operation, loading rates reached from 6.1 to 8.4 kg COD/(m^3·d) at 1.9% to 14.0% COD_{BW}/COD_{tot} in the influent, respectively. The variation in loading rate did not correlate with the increasing blackwater fraction at the inlet but was rather caused by the variations in the COD concentration of high-strength municipal wastewater (concentration peak). Furthermore, an increasing biogas quality from 60% to 71% (v/v) and COD removal efficiencies from 57% to 67% were reported during the investigated phases. The relatively high eliminations at low influent concentrations were ascribed to the possibility of solids accumulation in the reactor. The average effluent concentration ranged between 690 and 1.680 mg/L, so a direct discharge into receiving waters is not appropriate. The elimination of total solids ranged from 67% to 81%.

COD loading rates stayed below the proposed threshold value of 25 kg COD/(m^3·d) [27].

Due to a technical malfunction in the UASB during the last investigated transition state, a decrease in the methane concentration was observed. The malfunction was triggered by the accumulation of suspended solids inside the UASB reactor. It can be assumed that the total solids partially passed beyond the pellet sludge bed (reactor base), without being actually removed, and then accumulated in the upper part of the reactor. This hypothesis was corroborated by the observed decreased in the reactor's hydraulic performance and in methane degassing. Similar problems have been previously reported [28]; the same authors observed a COD accumulation of 25% (referred to COD influent load) and a COD conversion to methane of only 33%.

Fig. 2 gives an overview about the discussed results in both CSTR and UASB reactors. It can be inferred from Fig. 2 that methane concentrations are akin in both reactor configurations, yet UASB removal rates were lower, which can be attributed to the process malfunction. Moreover, single values oscillated much more expressively for the UASB due to varying composition and volume flows.

The obtained results show that blackwater co-digestion is suitable for anaerobic treatment of organic constituents in both CSTR and UASB reactors but insufficient to comply with European discharge standards, so a post-treatment is required. Under consideration of higher volume flows and the requirement of nitrogen elimination downstream, this is a notorious drawback for the UASB configuration.

3.3. Methane yield, methane production rate and methane content in biogas

In the CSTR, sewage sludge-based operation (start-up phase) resulted in a methane yield of 222 L CH_4/kg $COD_{removed}$, which aligns well with literature values for sewage sludge digestion. These were found to be within the range of 190–330 L CH_4/kg $COD_{removed}$ [29]. The increase of blackwater fraction at the reactor inlet led to an increase in the methane yield from 222 to 332 L CH_4/kg $COD_{removed}$ (Fig. 3). This was mainly attributed to lower organic loading rates at higher COD_{BW}/COD_{tot} ratios. In addition, synergistic effects among microorganisms associated with a co-digestion may play an important role as reported by Sosnowski et al. [26]. A constant methane concentration of approximately 60% (v/v) was reported for all investigated phases (Fig. 2). The process was not adversely affected by blackwater addition. For a sewage sludge-based digestion, typical methane concentrations in biogas vary from 60% to 70%. In addition, Wendland et al. [3] reported 75% methane in biogas for the anaerobic treatment of blackwater in a lab-scale CSTR reactor (Table 1).

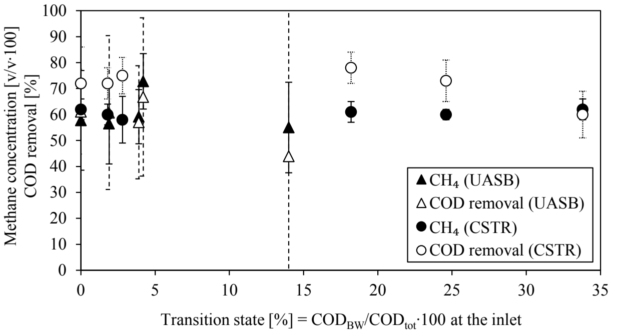

Fig. 2. Methane concentration in biogas and COD elimination during different transition states for CSTR (solid and empty circles) and UASB (solid and empty triangles) reactors. Bars indicate standard deviation of methane fraction, while dotted lines indicate standard deviation of COD elimination.

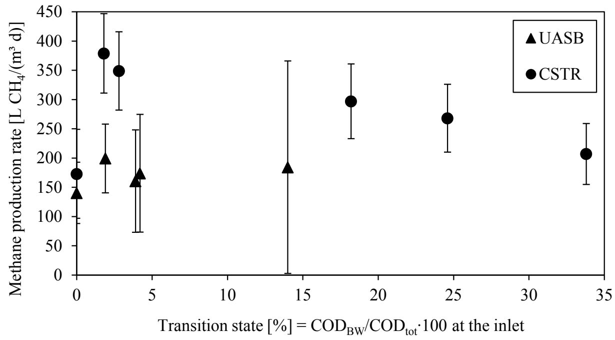

Fig. 4. Methane production rate during different transition states for CSTR and UASB reactors.

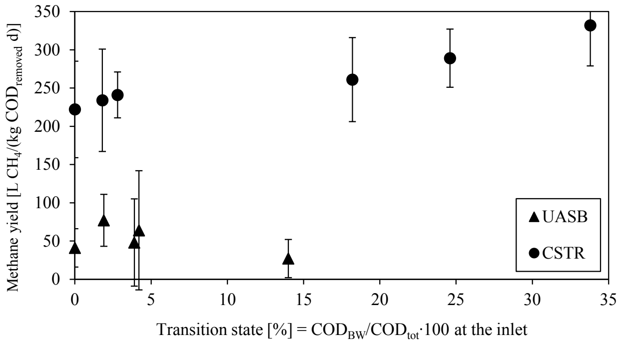

Fig. 3. Methane yield during different transition states of CSTR and UASB reactors.

de Graaff et al. [2] reported a methane concentration of 78% (v/v) for blackwater digestion in a UASB reactor. The increasing methane concentration in biogas generated in the UASB reactor investigated in this study indicates that increasing the blackwater fraction at the inlet led to an increase of the methane content towards 78%. For the UASB, the vast majority of the COD load accumulated in the upper part of the reactor and was not properly digested. The accumulation effect resulted in a low methane yield of 27–77 L CH_4/kg $COD_{removed}$. However, there is only limited data in the literature about the production of biogas from low-concentration wastewater, for instance, domestic wastewater, because in warm-climate regions usually the treatment is of interest – and not the gas production. This is mainly due to relatively low electricity prices in these regions (waterpower) [8,20–21]. Yet, it is known that dissolved methane can account for over 30%–40% of COD_{in} or correspondingly 50% of the methane produced [30], which justifies the need of degassing the effluent after anaerobic treatment [31]. In this study, comparably low COD conversion rates to biogas were observed in the UASB. Due to the modified design, it was not possible to determine when the accumulation of the suspended solids started. However, the permanent gap in the COD balance ($COD_{biogas} < COD_{in} - COD_{out}$) and the low methane yield indicate that the accumulation process began at an early transition stage. This problem cannot be attributed to UASB reactors in general, but rather to the modified design utilised within this study. Nevertheless, good COD removals rates were reported over all transition states investigated.

The methane production rate compares the daily methane production when normalised against the reactor volume. Specific methane production in the CSTR 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, thus decreasing with increasing blackwater fractions. These values are higher than those reported by Wendland et al. [3] for blackwater and, despite lower organic loading rates, in the same order of magnitude as in the municipal sewage sludge digestion (Table 1). This indicates that blackwater co-digestion in municipal digesters (plus post-treatment of process water in the aerobic stage of a WWTP) may be an interesting alternative for transition concepts towards source-separated sanitation.

For the UASB, no reliable statements could be made due to high standard deviations 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 (Fig. 4). In view of the obtained results for the UASB, it can be concluded that this technology is not interesting as full-flow process and technically inappropriate for transition to source-separated sanitation systems.

4. Conclusions and Outlook

- The findings of this study showed that, in addition to decentralised new pilot areas, transition strategies for resource-oriented sanitation must also address existing centralised wastewater infrastructure systems.
- Removal of organic matter was successfully carried out in both CSTR and UASB. For the CSTR, COD removal ranged from 60% to 78% up to a transition state of 35% (referred to COD_{BW}/COD_{tot} at the reactor inlet) was achieved. The UASB reached COD removal efficiencies of 57%–67% before process failure.
- Co-digestion of blackwater with PS and ES has proved to be more advantageous for the plant than the anaerobic treatment of high-strength municipal wastewater and blackwater. Generally, spare hydraulic reserves

(HRT > 20 d) are available in existing municipal digesters, which can be used for co-digestion. Additionally, for CSTR operation, the incremental blackwater displacement to the anaerobic stage favoured the methane yield, which increased from 222 to 332 L CH_4 kg/$COD_{removed}$ at 0% to 35% blackwater in the influent (COD_{BW}/COD_{tot}), respectively. For the UASB, no reliable statements concerning the methane yield could be made.

- Despite variations in substrate composition, a stable operation of the CSTR was reported, which was corroborated by constant methane concentrations in biogas of approximately 60% as well as COD removal efficiencies >60% during CSTR run.
- The co-digestion of blackwater from vacuum toilets in municipal digesters may considerably contribute to closing energy, nutrients and water cycles and improving sustainability in the wastewater treatment sector. However, individual planning according to the specific boundary conditions of the WWTP is necessary.

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