Sludge blanket anaerobic baffled reactor for source-separated blackwater treatment

Melesse Eshetu Moges, Daniel Todt, Eshetu Janka, Arve Heistad and Rune Bakke

ABSTRACT

The performance of a sludge blanket anaerobic baffled reactor was tested as an integrated treatment system for source-separated blackwater. The system consists of a stirred equalization tank, a buffer inlet tank, and two identical reactors, each with a working volume of 16.4 L, operated in parallel. Both reactors run at 3-days hydraulic retention time with different intermittent pulse feeding. Pulse lengths of 12 and 24 seconds per feed were set with respective rates of 114 L h^{-1} and 52 L h^{-1} for the short-pulse fed reactor (RI) and the long-pulse fed reactor (RII). Stable performance of the reactors was attained after 120 and 90 days, for RI and RII, respectively. After stable conditions attained, total chemical oxygen demand (COD) removal efficiency stabilized above 78%. Biogas production ranged from 0.52 to 1.16 L d^{-1} L^{-1} reactor volume, with 67–82% methane concentration and an average conversion of 0.69 ± 0.2 and 0.73 ± 0.2 g CH$_4$-COD g^{-1}COD$_{in}$ for RI and RII, respectively. The results imply that source-separated blackwater can be treated effectively in an anaerobic sludge blanket process on average loading rate of 2.3 ± 0.5 g COD d^{-1} L^{-1} reactor volume with high methane production potential and more than 80% removal of organic and particulate matter.

Key words | anaerobic digestion, blackwater, resource-recovery, sludge blanket, source-separation

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INTRODUCTION

Considering the increasing concerns of water scarcity and environmental pollution, a new trend has emerged for decentralized and source-separated approaches to processing wastewater as a resource. Source-separation of wastewater involves separate collection and treatment of the different domestic wastewater streams. About 70% of organic matter (chemical oxygen demand (COD)) and 80% of nutrients discharged by a household into the wastewater originate from toilets (Langergraber & Muellegger 2005; Kujawa-Roeleveld & Zeeman 2006; Todt 2015), which constitute only 1% by volume of the total domestic wastewater.

Recent studies on separate collection and treatment of blackwater (BW) fraction show that anaerobic upflow reactors have the potential for energy and nutrient recovery (Kujawa-Roeleveld & Zeeman 2006; Zeeman & Kujawa-Roeleveld 2011). The key feature of anaerobic upflow reactors is the formation of sludge blankets in which biomass and particulate organic matter are retained in the reactor. The upflow mode provides sufficient contact between anaerobic sludge and incoming substrate of the wastewater, thereby increasing the physical removal of suspended solids and biological conversion of dissolved organic compounds (Luostarinen & Rintala 2005). Understanding factors that influence those key features of upflow reactors will help to develop robust and effective treatment processes. The feasibility of sludge bed anaerobic processes for blackwater, therefore, depends primarily on: (i) the nature of the organic components in the blackwater, (ii) the operational conditions, particularly the organic loading rate (OLR), hydraulic loading rate (HLR), pH and temperature, and (iii) the reactor configuration, especially its capacity to retain biomass in the sludge bed.

The suspended solids content of blackwater is higher than what is considered suitable for upflow anaerobic sludge blanket (UASB) reactors so an anaerobic baffled

reactor (ABR) was applied. Studies with animal manure as feed have shown that feeds with high suspended solids content can be treated in sludge blanket ABR reactor at organic loading rates up to 400 g COD L^{-1} reactor d^{-1} at hydraulic retention time of 1.7 h (Bergland *et al.* 2015), which makes it potentially attractive for blackwater treatment. The performance of such a reactor principle, adapted for an integrated treatment system for source-separated blackwater, was tested here. The aim of this study was to evaluate effects of load and feed pulses on the system performance in terms of initial adaptation, stability, effluent quality, the removal efficiency of organic and suspended particulate matter, biogas production and methane yield.

METHODS

Collection and characterization of source-separated blackwater

The substrate used in this anaerobic digestion experiment is source-separated blackwater (BW) collected from student dormitories at the Norwegian University of Life Sciences with 48 inhabitants. The dormitory is equipped with vacuum toilets with 1.2-L flushing volume. A vacuum pump with an integrated grinder (Vacuumarator^{TM} 25MB, Jets, Hareid, Norway) delivers the BW to a pumping station from which it is transferred with an impeller pump (40U, Tsurumi Europe GmbH, Düsseldorf, Germany), into a stirred storage tank located in the laboratory facility. Total retention time in the sewer system is 36–48 h. More details are given in Todt *et al.* (2015). Samples were taken from this tank on weekly bases to study and the composition of this BW was analyzed according to standard methods as described in the Liquid analysis section.

Reactor configuration and setup

Figure 1 displays the schematic flow of the experimental setup. The experimental set up consists of a continuously stirred raw BW storage tank, a buffer tank and two cylinder shaped laboratory-scale two stage sludge blanket anaerobic baffled reactors with a working volume of 16.4 L each. The reactors were constructed from 10 mm thick PVC pipe section with an internal structure to establish two chambers. The first chamber has internal dimensions of 315 mm height and 315 mm diameter. The buffer tank has a working volume of 12 L with a retention time of 8 h. The pH in the buffer tank lowered to an average

of 7.4 ± 0.6 from the inlet blackwater pH of 9 ± 0.3. The temperature in the buffer tank ranged from 10 to 15 °C in the winter time and from 18 to 21 °C during the summer time. The feed enters from the buffer tank to the bottom of the first chamber of the reactors using peristaltic pumps. The blackwater flows from the top of this first chamber, directed by a baffle, to the bottom of a smaller chamber of 245 mm height and 135 mm diameter, therefore defined as an ABR. One-third of the second chamber is used for down flow and remaining two-thirds is used for upflow. The reactors were fed intermittently with 16 pulses per day with partially hydrolyzed blackwater from a buffer tank using peristaltic pumps. Two different pulse lengths, 12 and 24 seconds per pulse, were applied for Reactor I and Reactor II, respectively. The hydraulic load was 6 L d^{-1} for both reactors and flow rates were set at 114 L h^{-1} for the short-pulse fed reactor (RI) and 52 L h^{-1} the long-pulse fed reactor (RII). The flow rate was set by adjusting the rotation speed of the peristaltic pumps with help of a frequency converter. The flow velocities in the compartments were calculated based on the pulse volume, pulse length and related cross-section area. A water lock on the outlet was used to separate the produced gas from the effluent liquid. The reactor temperature was adjusted to stay within the 25 and 28 °C range with help of a heated water bath to keep the reactors at a constant temperature. The reactors were inoculated with the same sludge from previous experiment. One-third of the operational volume was filled with inoculum.

Liquid analysis

Inlet raw blackwater and digested effluent samples were taken on a weekly basis in form of 24 h composite samples. Samples were also taken at the bottom of the two chambers in each of the reactors every 2 to 3 weeks to sample and analyze the sludge. Analysis of chemical oxygen demand, both total (CODt) and soluble (CODs), pH, total ammonia nitrogen (TAN), total and soluble phosphorus (P-tot and PO_4-P), total suspended solids (TSS), total solids (TS), volatile solids (VS), volatile suspended solids (VSS), and measurement of the concentration of volatile fatty acids (VFAs) were carried out to determine the characteristics and efficiency of the system. Total COD and total P were measured from the unfiltered sample. Soluble COD, PO_4-P, and TAN were measured from filtered samples using 1.2 μm glass fiber filters. CODt and CODs concentrations were analyzed using spectrophotometric test kits (Hach-Lange, Berlin, Germany) LCK 014 and LCK 514, respectively. Total P, PO_4^{-3}-P, and
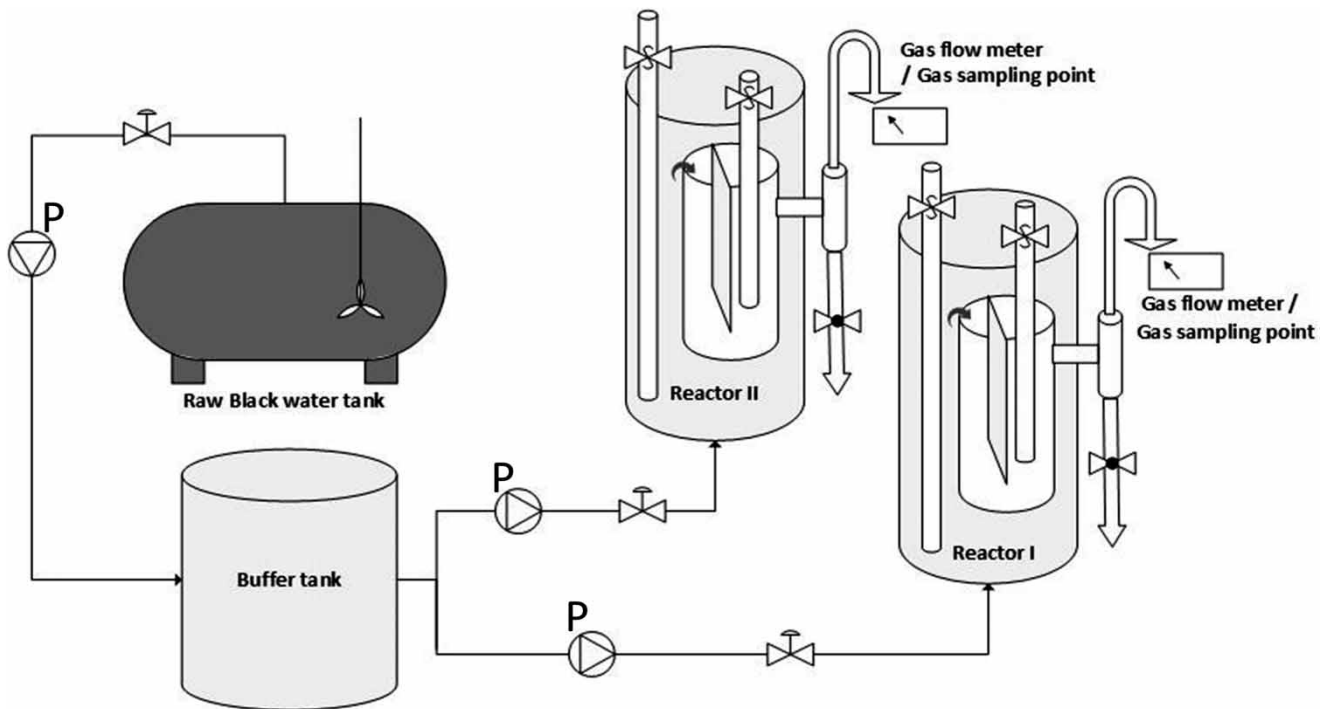
Figure 1 | Flow scheme of the experimental setup. P indicates pumps and the valve signs indicate sampling points.

NH_4-N in the filtered samples were diluted (with a dilution factor of 10^3) and analyzed using Hach-Lange test kits of LCK 349 and LCK 304, respectively.

TSS and VSS retained on the 1.2 μm glass fiber filters (Whatman GF-C, GE Healthcare, Little Chalfont, UK) and TS and VS were determined using standard methods (American Public Health Association (APHA) 2005). Settling rate of effluent sludge was measured as volume of settled sludge per L effluent sample both after 5 min and 30 min (standard for the sludge volume index (SVI)) to obtain more information about settling rate than SVI alone. For VFA analysis, samples were centrifuged at 6,000 rpm for 10 min and the supernatant was filtered through 0.45 μm membrane filter prior to analysis. VFA was analyzed using gas chromatography (HP 6890 serial C) with a flame ionization detector and a capillary column DB-FFAP 30 m long, inner diameter 0.25 mm and 0.25 μm film. Helium was used as the carrier gas, with flow velocity of 23 mL/min. The detector gases were hydrogen and air. The injector and the detector temperatures were set to 200 °C and 250 °C, respectively. The oven was programmed to hold at 80 °C for 1 min, go to 100 °C at a rate of 15 °C/min, and then to 230 °C at a rate of 100 °C/min (Bergland et al. 2015).

Biogas monitoring

Biogas production, from both reactors, was monitored daily. The gas volume was measured continuously using Ritter® MilliGas counter (Dr.-Ing. Ritter Apparatebau GmbH & Co. KG). Gas samples were collected using 1 L collection bag (7˙x7˙ multi-layer RESTEK, Bellefonte, USA) for CH_4 and CO_2 determination. Biogas composition, as methane (CH_4) and carbon dioxide (CO_2), was measured using Agilent Technology 3000A Micro Gas Chromatograph (Agilent Technologies Inc., Germany). The gas chromatograph comprised of a micro injector, thermal conductivity detector and a high-resolution capillary column. Helium was used as the carrier gas at a flow rate of 17 mL min^{-1}.

Methane production as COD mass load in the biogas (COD_{CH4}) was calculated from the average measured methane CH_4 fraction (partial pressure of methane) in the biogas (fCH_4 in Pa), the daily cumulative gas flow rate ($Qgas$ m^3/d), and the theoretical oxygen demand for CH_4 $TOD(CH4)$ (64 g COD_{CH4} mol^{-1}). R is the universal gas constant (8.3145 m^3 Pa mol^{-1} K^{-1}) and T is operational reactor temperature (°C)).

$$CODCH4 = \frac{fCH4*\text{Qgas}}{R*(T+273)}*TOD(CH4) \tag{1}$$

Mass balance calculation

A Microsoft Excel COD mass balance sheet was created to calculate the COD mass balance with the COD mass loading (g O_2 d^{-1}) determined for the inlet (COD_{in}), effluent (COD_{out}), excess sludge (COD_{sludge}, removed infrequently to sample the sludge) and gas (COD_{CH4}). OLR is expressed as the daily load of organic matter determined as COD normalized per reactor volume unit (g O_2 $L^{-1}d^{-1}$) where Q is the hydraulic load in L d^{-1}; Ccod is the COD concentration in g L^{-1} at the particular sampling point and a working volume of the reactor in L (Vr):

$$OLR = \frac{Q*\text{Ccod}}{Vr} \qquad (2)$$

COD accumulated in the reactor in form of biomass/ sludge (COD_{acc}) was then calculated from the OLR at COD_{in}, COD_{out}, $COD_{sludge,}$ and COD_{CH4}. All of the given mass balance figures are normalized per reactor volume unit (g O_2 d^{-1} L^{-1} working volume).

$$CODacc = COD(in - out) - CODCH4 - CODsludge \qquad (3)$$

Statistical analysis

Analysis of variance (ANOVA) test (using Minitab 17 Statistical Software, Minitab, 2017) was performed to test whether the two feed pulse lengths of treatment and variation on organic loading have any significant effect on the performance of the process. Before ANOVA analysis, the data were checked to see whether they satisfied the conditions of normality and equality of variance required for ANOVA. The distribution of residuals was very similar at all levels and the normality plot showed that the residuals lie close to the diagonal line, which represent the ideal normal distribution. The distribution of the residuals further tested using Anderson-Darling Test for Normality. Test for equal variance was also performed using Leven's Test. Both the conditions of normality and equality of variance were satisfied to perform ANOVA.

RESULTS AND DISCUSSION

The raw blackwater (BW) composition used in this research is presented in Table 1 and is characterized by organic matter concentration measured as CODt, CODs, TSS, TS, VS, pH, volatile fatty acid, ammonium nitrogen and phosphorus. The total COD concentration in the influent

Table 1 | The composition of BW used as feed for the reactors during the experimental period

Parameter	Unit	Average
pH		9 ± 0.3
CODt	mg/L	$5,500 \pm 1,300$
CODf	mg/L	$1,200 \pm 330$
TSS	mg/L	$3,000 \pm 900$
TS	mg/L	$6,300 \pm 700$
VFA	mg/L	400 ± 200
VS	mg/L	$4,800 \pm 600$
NH_4-N	mg/L	900 ± 180
Tot P	mg/L	120 ± 20
PO_4^-P	mg/L	60 ± 20

The $\pm$ shows the standard deviation.

ranged between 1,900 and 7,600 mg/L, and the corresponding soluble COD concentrations were in the range between 400 and 2,300 mg/L. The average of the influent particulate COD ratio ((CODt-CODs)/CODt) ratio remained relatively high (0.8 on average) throughout the operation. The influent COD is therefore mainly particulate and constitutes about 77% of the total COD. Similar blackwater composition results are also reported (Murat Hocaoglu *et al.* 2010; Todt *et al.* 2015). The COD of the filtered sample, defined as the soluble fraction, constitute only about 23% of total COD.

The influent TSS concentration ranged from 1,000–5,900 mg/L. The high standard deviation of COD and TSS indicates the significant temporal variability of raw BW composition during the study period. The variations in BW composition could arise from several factors including the diet of the inhabitants, toilet paper consumption and numbers of flushing events per toilet visit.

COD removal efficiency

During the start-up phase that lasted about 5 months, the removal efficiency of total COD varied from 24 to 67% with an average of 48% in RI and from −4 to 74% with an average of 36% in RII (Figure 2 top). Suspended particulate COD fraction removal during this stage of the operation was on average 68 and 76% for RI and RII, respectively. The filtered COD fraction (CODs) removal was negative for the first 3 months (Figure 2 bottom), implying a greater hydrolysis rate of accumulated organic matter compared to the methane production rate during the first 120 days of operation.

The surplus dissolved organics in the effluent compared to influent dissolved organics diminished with time and
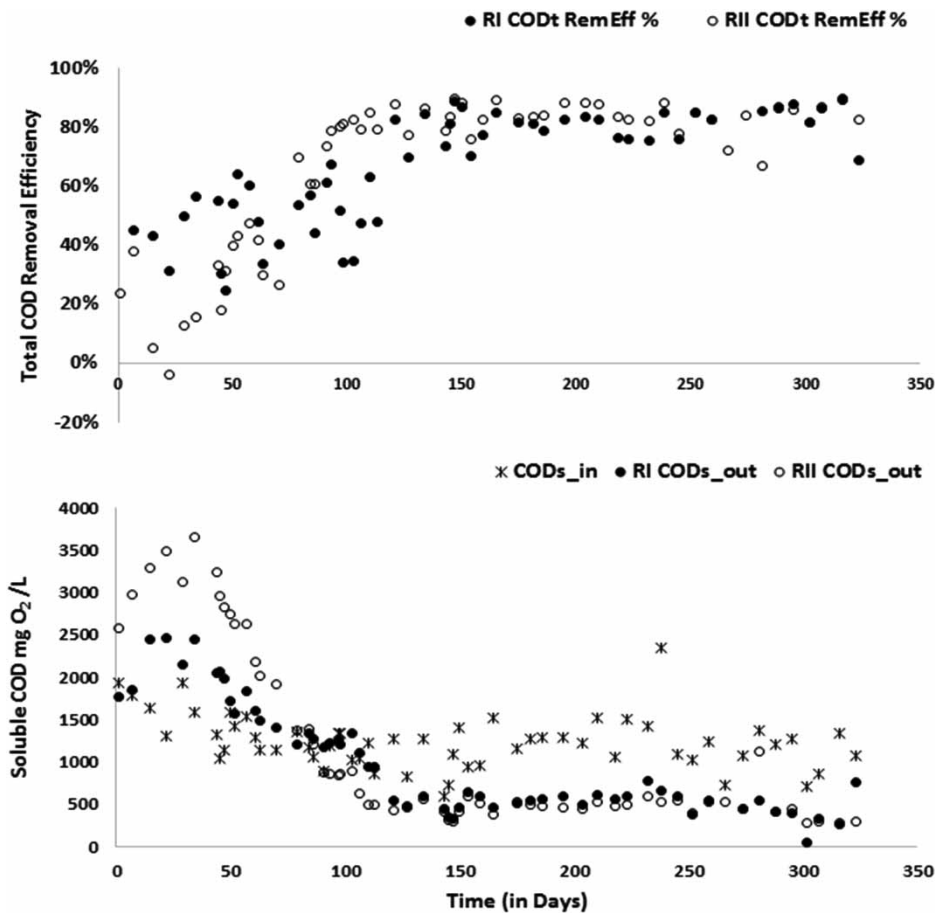
Figure 2 │ Total COD removal efficiency (CODt RemEff %) in RI and RII (top), and measured soluble COD (CODs) in and out of the reactors (bottom) during the start-up and after stable performance.

reached stable condition after 120 and 90 days for RI and RII, respectively (Figure 2 bottom). During this period, both particulate and soluble organic fraction removal stabilized with an average removal efficiency of 86 and 90% for particulate COD and 55 and 54% for the soluble fraction in RI and RII, respectively. This implies that the sludge blanket–ABR reactor configuration achieved efficient retention and degradation of particulate organic matter.

Effect of organic loading rates

During the stable condition period, the two reactors received on average an organic load of 38 ± 7 g O_2 d^{-1} and $28. \pm 10$ g O_2 d^{-1} COD for RI and RII, respectively. This translates into an OLR normalized per reactor volume of 2.3 ± 0.5 and 1.6 ± 0.6 g O_2 d^{-1} L^{-1}, respectively. The variability of the organic load was more pronounced in RII than RI (Figure 3) and likely a result of different flow velocities out of the buffer tank during feeding, which were 610 m/h and

320 m/h for RI and RII, respectively. However, this difference did not influence the effluent quality at stable conditions. Both reactors achieved similar COD removal efficiencies ($p = 0.197$) and had comparable ($p = 0.588$) methane conversion rates of 0.69 and 0.73 g CH_4-COD g^{-1}CODin L^{-1} reactor volume for RI and RII, respectively.

Effects of feed pulse length

It can be seen from Figure 4 that effluent sludge settling rate at 5 min and 30 min of sedimentation for both RI (top) and RII (bottom) were similar. Most of the effluent sludge from both reactors settled within 5 min. Hence, the change in the volume of effluent sludge between 5 and 30 min sedimentation time was insignificant ($p = 0.81$ for RI and $p = 0.66$ for RII). The settled effluent sludge volume was higher for RI than in RII except for the first few days. However, after a stable condition was reached, the effluent sludge volume in both reactors were close to zero.
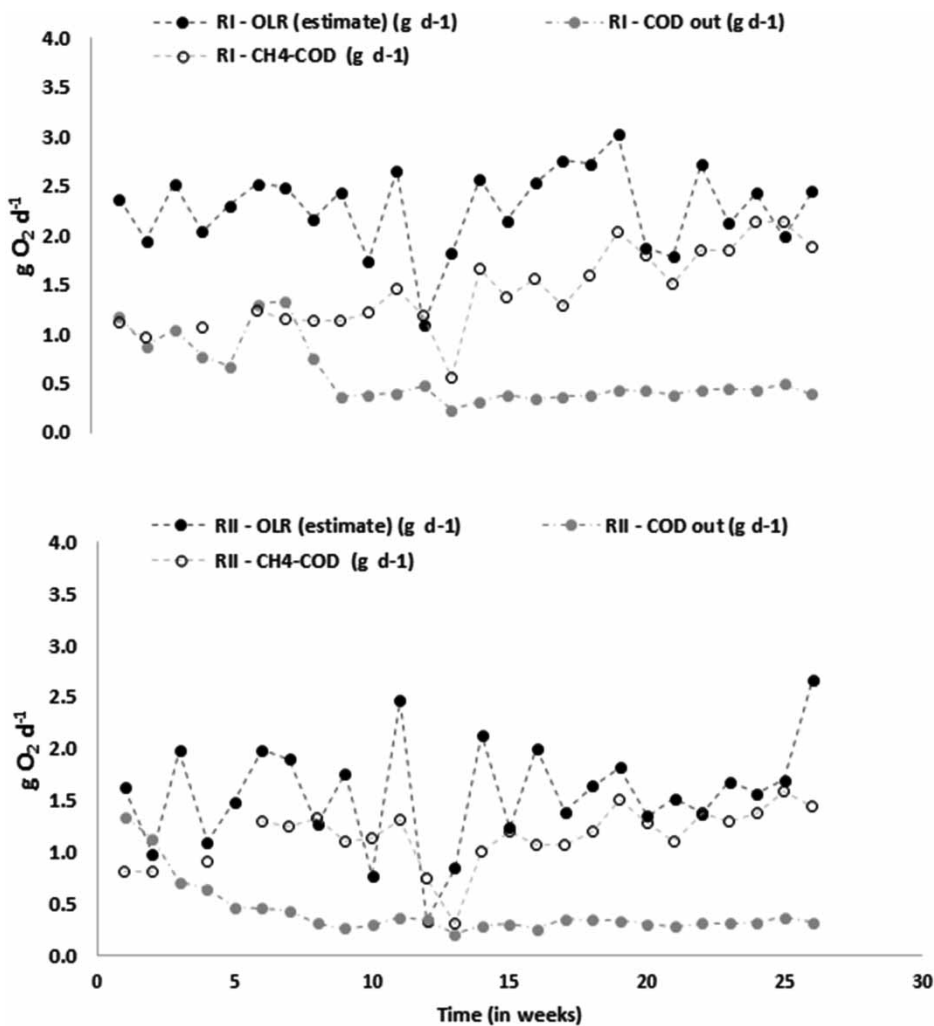
Figure 3 │ COD mass loading rates, normalized per liter reactor volume for inlet, gas (CH$_4$) and effluent for RI (top) and RII (bottom).

The upflow velocity plays an important role in determining the behavior of sludge development in sludge beds and sludge blanket expansion (Wiegant 2001; Mahmoud 2002; van Lier *et al.* 2008). In our reactors, the upflow velocity is determined by the actual flow rate during pulse feedings of 114 L h^{-1} and 52 L h^{-1} resulting in an upflow velocity of 1.5 and 0.7 m h^{-1} for RI and RII, respectively. The up-flow water velocity usually ranges between 0.1 and 1.4 m h^{-1} in UASB reactors (Korsak 2008). The high rate of flow in this study lasts, however, only for a very short time for 12 and 24 seconds per pulse with 90 min long pulse intervals. The average upflow velocity was therefore much less than this actual pulse upflow velocity. It is calculated that the high flow rate, during pulse feed, lifts the sludge blanket by about 6 mm but it slowly sinks between the pulses. In unmatured reactors, this may cause instability

and removal of more biomass to the effluent, which is especially the case at the startup stage in RI, requiring a longer time to reach steady. Stable condition was reached sooner for the less intense feed pulse (RII) than for the high flow pulse (RI). Studies on the effect of upflow velocity on suspended solid removal indicated deterioration of effluent quality as upflow velocity increases from 0.7 to 0.9 m/h to 3.2 m/h (GonÇalves *et al.* 1994). However, no differences in residual sludge volume were observed in the effluents of the two reactors (RI vs RII) after a stable condition was achieved (Figure 4) where, in both cases, effluent sludge volume was close to zero. Both reactors showed further a comparable COD removal efficiency (Figure 2), implying that the reactors had sufficient sludge expansion volume, solid separation and mass transfer capacity for both feed pulses tested.
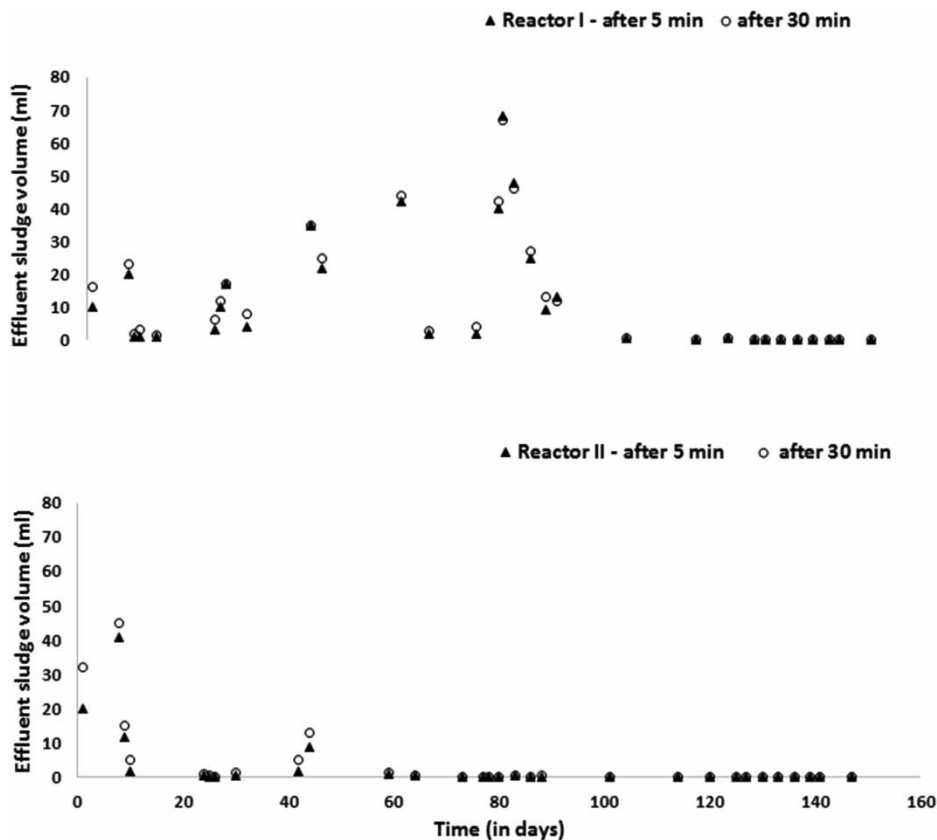
Figure 4 | Effluent sludge volume of RI (top) and RII (bottom) at 5 and 30 min of sedimentation time during the study.

Production and influence of volatile fatty acid

Start-up period

The organic substrates present in the blackwater were subjected to simultaneous hydrolysis and acidification by hydrolytic and acidogenic bacteria in the feed buffer tank, reflected in low pH at the bottom of the buffer tank and formation of VFA. Acetate was the prime VFA constituent in the buffer tank, as well as in the different parts of the reactors and effluents. The ratio of acetate to total VFAs reached up to 93% with an average of 71 ± 15%, which shows high efficiency of acidogenic and acetogenic bacteria. Acetate is produced in anaerobic biodegradation of carbohydrates, protein, and fats (Narkis *et al.* 1980). During this start-up phase, total VFA concentrations in the reactor effluent were higher (with an average of 893 ± 473 mg/L for R I, and 1,700 ± 561 mg/L for RII) than the feed blackwater (440 ± 234 mg/L) and reached peak value after 2 months in both RI than RII (Figure 5). This demonstrates that the establishment of methanogenesis was lagging behind acidogenesis due to the slow growth rate of methanogenic archaea. Effluent VFA decreased sharply towards the end of the start-up period and all the acetate produced was converted into methane after stable condition attained. The concentration of VFA in the effluent also corresponds with the aforementioned filtered COD (CODs) concentrations of the effluent (Figure 2 bottom). Propionic acid concentration was also relatively high in the blackwater but lower in the reactor effluents, implying that methanogenesis was the overall rate-limiting step until the stable condition reached.

Stable performance period

The methane production progressively increased when the reactors matured and 60–70% of the feed COD was converted to methane. Effluent VFA concentrations decreased and the COD and TSS removal reached up to 89 and 90%, respectively. Figure 6 shows the average VFA concentration after a stable condition is attained from the inlet tank, buffer tank and the two chambers of the two reactors.

The concentration of VFA in the buffer tank reached a peak value of 4,750 mg/L and had higher values than the
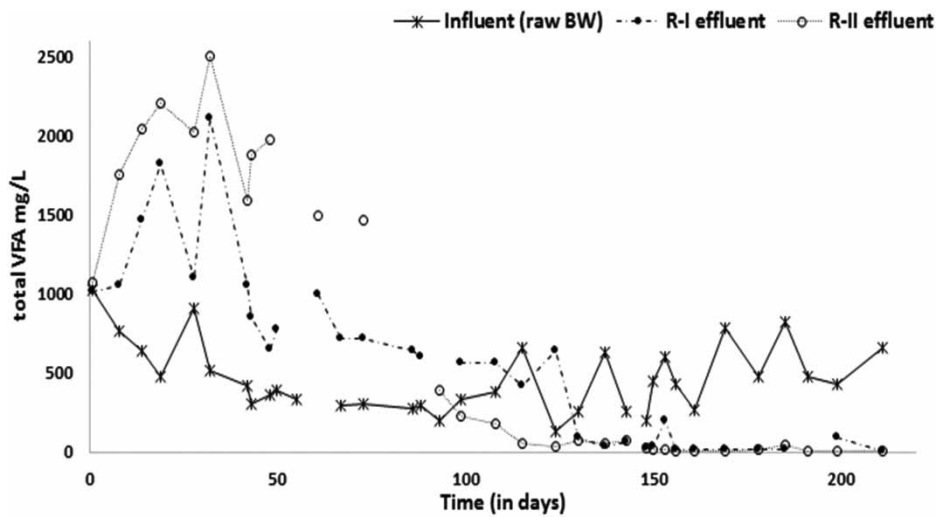
Figure 5 | Total VFA in the influent (raw blackwater) and effluents of RI and RII during the start-up period and after a stable condition was attained.
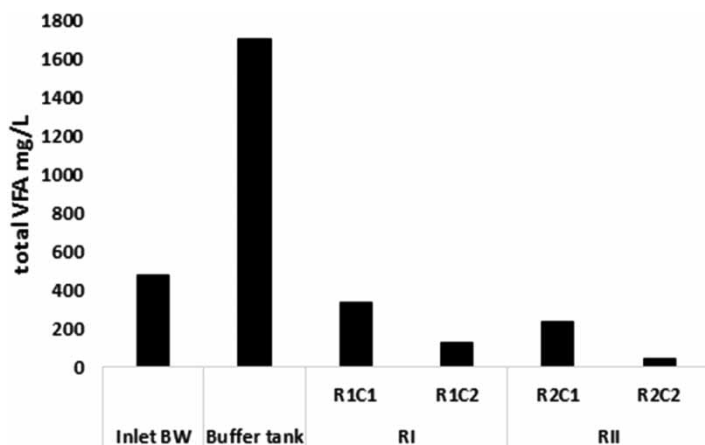

Figure 6 | Average total VFA with standard deviation of 238, 204, 125, 42, 109, and 27 in the inlet blackwater, buffer tank, and different compartments of RI and RII, respectively (where R1C1 = reactor 1 compartment 1, R1C2 = reactor 1 compartment 2, R2C1 = reactor 2 compartment 1, R2C2 = reactor 2 compartment 2).

raw blackwater throughout the operation period, but degraded very rapidly in the reactors. The buffer tank, therefore, serves as a pre-hydrolysis and fermentative step. Most of the VFA was removed in the first reactor compartment and it was almost completely removed in the effluent (compartment 2). Such VFA concentration levels indicate the stability of the reactors (de Mes *et al.* 2003; Colón *et al.* 2015). VFAs can be considered reliable for process monitoring (Murto *et al.* 2004).

pH

Overall, in both reactors pH remained stable for most of the time both in the influent and in the effluent during the operation period. This is mainly due to the

high buffer capacity (alkalinity of 560 ± 58 mg/L CaCO3), as well as high ammonium concentration (851 ± 174 mg/L NH4-N) in the influent. The average pH of the influent was 9.1 ± 0.3 and the corresponding pH for the effluent of RI and RII was 8.4 ± 0.2 and 8.1 ± 0.3, respectively. In AD, pH is a key factor in the formation and characterization of VFA and the ammonium/free ammonia equilibrium (Ortiz *et al.* 2014).The pH influences bacterial and archaeal growth rates (Espinoza-Escalante *et al.* 2009). Acetate was the main product of acidogenic degradation in the buffer tank and was also the main VFA component in the different reactor compartments and effluents. In such highly buffered systems, pH changes were small even if VFA varied considerably.

Effluent quality

To investigate the influence of feed pulse length on the effluent quality of the sludge blanket ABR, the reactor performance and effluent quality of the two reactors were compared. The effect of differences in feed pulse length was observed at the start-up period. However, the removal efficiencies of the two reactors demonstrated no significant effects on effluent quality after a stable condition was attained. The results of TSS, CODt, CODs, and VFA removal efficiencies were similar in both reactors at a confidence interval of 95% with p-values of 0.241 and 0.197 for TSS and COD, respectively. Likewise, the effluent concentrations of NH_4-N (926 ± 113 mg/L for RI and 959 ± 188 mg/L for RII), and PO_4-P (84 ± 12 and 87 ± 17 mg/L for RI and RII, respectively) in both reactors were comparable but much higher than the concentrations in the raw blackwater (851 ± 174 mg/L NH_4-N and 60 ± 17 mg/L PO_4-P). Hence, the system produced excess soluble N and P in the effluent, which opens up the opportunity to recover these valuable resources with novel post-treatment steps.

Mass balance and potential methane recovery

Biogas production

Biogas production and methane content were measured and compared between the two reactors. Biogas production ranged from 8.6 to 19 L d^{-1} in RI and 6 to 10 L d^{-1} for RII, with an average methane content of $70 \pm 6\%$ and $74 \pm 8\%$, respectively. The biogas production variations were attributed to organic loading fluctuation. High biogas yield and methane content in the present study can be attributed to a combination of reactor configuration, feed composition and significant pre-hydrolysis in the buffer tank. The methane content in this sludge blanket anaerobic baffle reactor was higher compared to some other systems such as conventional UASB with biogas methane content fluctuating between 40 and 60% (Yu *et al.* 2002), but comparable to reported biogas yield in co-digestion of blackwater (Elmitwalli *et al.* 2002) and in a 'MIX-UASB reactor' (Terva-hauta *et al.* 2014). The study shows that biogas with high methane content can be recovered from source-separated blackwater under conditions tested here.

COD mass balance

Figure 7 presents steady state COD mass balance for the two reactors. The cumulative organic load after stable condition was achieved 0.30 and 0.21 kg COD with an average daily normalized OLR of 2.3 and 1.6 g O_2 d^{-1} L^{-1} reactor volume and a hydraulic loading of 681 and 718 L for RI and RII, respectively. The amount of COD retained or accumulated as biomass in the reactors were 14% for RI and 5% for RII implying slow build-up of the sludge bed. In the 18 weeks of stable performance period, only 1.1 and 1 L of sludge was removed from RI and RII, respectively, This is beneficial from the operational point of view, as it demonstrates that the process requires little withdrawal of excess sludge. Lower retained COD in RII is attributed to the higher conversion of COD to methane and more effluent COD. Residual COD fractions in the effluents were 17% and 20% in RI and RII, respectively.

During the stable condition period, an average of 1.60 ± 0.06 g O_2 COD d^{-1} L^{-1} reactor volume and 1.20 ± 0.02 g O_2 COD d^{-1} L^{-1} reactor volume was converted to CH_4 in RI and RII, respectively. This translates into a methane conversion rate of 69% and 73% relative to the inlet COD load. This is high compared to other studies on concentrated blackwater where only 40% of the incoming COD load converted to biogas, while 40 to 50% was accumulated as non- or slowly-degradable matter and 10 to 20% washed out from the system (Verstraete *et al.* 2009). The high biogas yield in the present study can be attributed to a combination of reactor configuration, feed composition, pulse feeding and significant pre-hydrolysis in the buffer tank. The study shows the potential of methane recovery from the source-separated blackwater with 3 days of hydraulic retention time.

CONCLUSIONS

In this study, source-separated blackwater was anaerobically treated with a sludge bed anaerobic reactor at controlled temperature (i.e. 25 to 28 °C) for several months, going from variable efficiency to steady-state in less than half a year. The results revealed that concentrated source-separated blackwater was treated efficiently at 3 d hydraulic retention time (HRT) with total COD removal efficiency stabilized above 78% at steady state. Biogas production ranged from 6 to 19 L d^{-1} and an average conversion of 0.69 and 0.73 g CH_4-COD $g^{-1}COD_{in}$ at steady-state for the two reactors operated with different feed pulses. Feed pulse length influenced significantly the early phase of the AD process. Short and strong feed pulse resulted in a more unstable performance at start-up phase and longer time to reach stable condition compared to the longer pulse feeds with lower flow rate, but similar steady-state
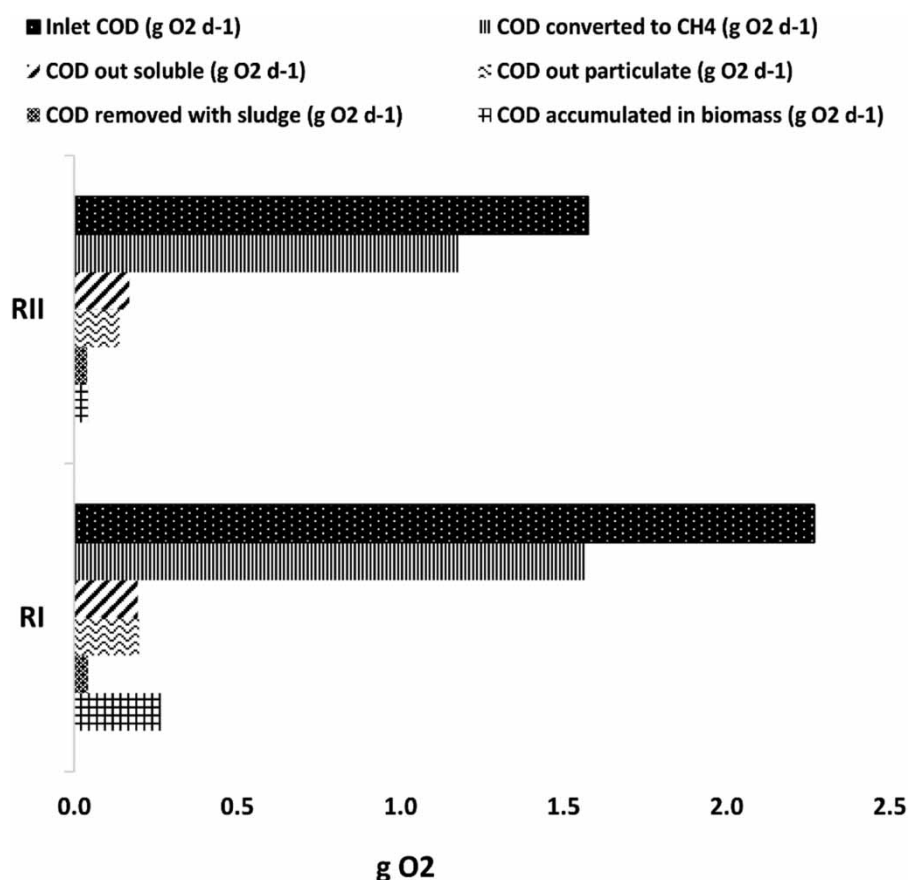
■ Inlet COD (g O2 d-1)   **Ⅲ** COD converted to CH4 (g O2 d-1)

◪ COD out soluble (g O2 d-1)   **⩔** COD out particulate (g O2 d-1)

▩ COD removed with sludge (g O2 d-1)   **⊞** COD accumulated in biomass (g O2 d-1)

Figure 7 | The COD mass balance of RI and RII at steady state.

performances were observed for the two feed pulses. Although gas production was mainly influenced by the uncontrolled change in the influent composition, the biogas methane concentration was quite stable. The results imply that source-separated blackwater can be treated effectively in an anaerobic sludge blanket process at an average loading rate of 2.3 g COD $d^{-1} L^{-1}$ reactor volume with high methane production and removal of organic particulate matter. It also revealed that the reactors had sufficient sludge expansion volume, solid separation and mass transfer capacity for both feed pulses tested.

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