Anaerobic stabilisation of urine diverting dehydrating toilet faeces (UDDT-F) in urban poor settlements

Biochemical energy recovery

Riungu, Joy; Ronteltap, Mariska; van Lier, Jules B.

DOI
10.2166/washdev.2019.099

Publication date
2019

Document Version
Final published version

Published in
Journal of Water Sanitation and Hygiene for Development

Research Paper

Anaerobic stabilisation of urine diverting dehydrating toilet faeces (UDDT-F) in urban poor settlements: biochemical energy recovery

Joy Riungu, Mariska Ronteltap and Jules B. van Lier

ABSTRACT

Biochemical energy recovery using digestion and co-digestion of faecal matter collected from urine diverting dehydrating toilet faeces (UDDT-F) and mixed organic market waste (OMW) was studied under laboratory- and pilot-scale conditions. Laboratory-scale biochemical methane potential (BMP) tests showed an increase in methane production with an increase in OMW fraction in the feed substrate. In subsequent pilot-scale experiments, one-stage and two-stage plug flow digester were researched, applying UDDT-F:OMW ratios of 4:1 and 1:0, at about 10 and 12% total solids (TS) slurry concentrations. Comparable methane production was observed in one-stage ($R_{o\text{-}4:1,12\%}$) (314 ± 15 mL CH_4/g VS added) and two-stage ($R_{am\text{-}4:1,12\%}$) (325 ± 12 mL CH_4/g VS added) digesters, when applying 12% TS slurry concentration. However, biogas production in $R_{am\text{-}4:1,12\%}$ digester (571 ± 25 mL CH_4/g VS added) was about 12% higher than in $R_{o\text{-}4:1,12\%}$, significantly more than the slight difference in methane production, i.e. 3–4%. The former was attributed to enhanced waste solubilisation and increased CO_2 dissolution, resulting from mixing the bicarbonate-rich methanogenic effluent for neutralisation purposes with the low pH (4.9) influent acquired from the pre-acidification stage. Moreover, higher process stability was observed in the first parts of the plug flow two-stage digester, characterised by lower VFA concentrations.

Key words | anaerobic digestion, biogas production, co-digestion, informal settlements, UDDT faeces

Joy Riungu (corresponding author)
Mariska Ronteltap
Jules B. van Lier
Environmental Engineering and Water Technology Department,
IHE Delft Institute for Water Education,
Westvest 7, 2611 AX Delft,
The Netherlands
E-mail: *rnyawirah@yahoo.com*

Jules B. van Lier
Faculty of Civil Engineering and Geosciences, Department of Water Management, Sanitary Engineering Section,
Delft University of Technology,
Stevinweg 1, 2628 CN Delft,
The Netherlands

INTRODUCTION

As an innovative solution to enhance sanitary conditions in informal settlements in low income countries, urine diverting dehydrating toilets (UDDTs) have been adopted (Austin & Cloete 2008; Niwagaba *et al.* 2009a; Schouten & Mathenge 2010; Katukiza *et al.* 2012). Such is also the approach adopted by Sanergy, a social enterprise working on sanitation improvement within informal slum settlements, in Nairobi, Kenya. Sanergy fabricates and installs the Fresh Life© toilets in collaboration with entrepreneurs in the slums who maintain them. Currently, approximately 7,000 kg of faeces is collected from the UDDTs, further referred to as UDDT-F, and delivered to a central treatment plant on a daily basis. Owing to the high pathogenic levels in human waste (Feachem *et al.* 1983), an extra pathogen inactivation step is required especially when the faecal matter will be valorised for agricultural purposes. A number of different treatment technologies were developed for source separated human

doi: 10.2166/washdev.2019.099

faeces and include plain storage, composting, black soldier flies, chemical treatment, vermi-composting and anaerobic digestion (AD) (Vinnerås 2007; Niwagaba *et al.* 2009b; Rajagopal *et al.* 2013; Strande *et al.* 2014; Fagbohungbe *et al.* 2015). The main treatment technology applied by Sanergy for UDDT-F is composting, producing an end product that is sold as organic manure (Evergrow@), available on the Kenyan market. Moreover, the increasing amount of collected UDDT-F on a daily basis sparked a need for diversification of the treatment options.

The potential for application of AD at any scale and almost any place (Van Lier *et al.* 2008; Pabón-Pereira *et al.* 2014), marked the decision to select AD as a faecal waste treatment option in informal slum settlements. In addition, by means of AD, the chemically stored bio-energy in the organic waste can be recovered as biogas, providing an alternative fuel for local use (Abbasi *et al.* 2012). AD is considered an efficient technology for the stabilisation of organic wastes, producing a digestate with a high fertiliser value (Berndes *et al.* 2003; Martín-González *et al.* 2010; Park *et al.* 2016). The key reported drawback in AD is inadequate pathogen inactivation (Kunte *et al.* 2000; Chaggu 2004; Horan *et al.* 2004; Massé *et al.* 2011; Chen *et al.* 2012; Fagbohungbe *et al.* 2015) and low methane production especially from human faecal matter (Rajagopal *et al.* 2013; Fagbohungbe *et al.* 2015). It must be noted that the microbiological safety of the digestate and treated sludge is essential as it has implications for human health and cycling of pathogens in a densely populated environment through the food chain (Avery *et al.* 2014). As such, this study is part of a wider research on the potentials for the anaerobic stabilisation of UDDT-F, enhancing biogas production and pathogen inactivation, with the present paper focusing on the production of another side-product next to hygienised sludge, i.e. biogas.

In our previous study, we evaluated the accumulation of volatile fatty acids and their effect on pathogen inactivation during the digestion of UDDT-F and mixtures of UDDT-F and organic market waste (OMW) in a one- and two-stage plug flow anaerobic digester (Riungu *et al.* 2018b). Results showed higher pathogen inactivation in the two-stage plug flow digester, with the digestate meeting WHO standards of 1,000 CFU/100 mL, applying a solids retention time (SRT) of 29 days. The used OMW, widely available and at close proximity to UDDT-F source, is characterised by a vast readily degradable organic fraction (Zhang *et al.* 2008; Riungu *et al.* 2018a). In addition to sludge hygienisation, the production of an alternative fuel (biogas) from the faecal matter will very likely accelerate the acceptance of the proposed technology. As such, the research described herein focused on the potential for biogas production during anaerobic stabilisation of UDDT-F using laboratory-scale biochemical methane potential (BMP) tests and pilot-scale plug flow one- and two-stage anaerobic digesters. Under pilot-scale experiments one-stage and two-stage plug flow digesters were researched, applying UDDT-F:OMW ratios of 4:1 and 1:0, at about 10 and 12% total solids (TS) slurry concentrations.

MATERIAL AND METHODS

Materials

UDDT-F waste samples

UDDT-F samples used for this study were obtained from the Fresh Life® UDDT within Mukuru Kwa Njenga/Mukuru Kwa Reuben informal slum settlement, Kenya. Fresh Life@ toilets are offered on a pay-and-use basis in the form of serviced shared facilities, charging between 0.05–0.1 euros per use. Within each toilet facility, a 30 L container is used for waste collection, with approximately 10 g sawdust added by the user after every toilet use. The toilets are emptied on a daily basis, where used containers are replaced by clean ones. Five containers with UDDT-F were randomly selected after which mixing of the contents was done in order to obtain a homogeneous mix.

Organic market waste samples

OMW was collected from vegetable vendors, eating points and waste disposal points within Mukuru Kwa Njenga and Mukuru Kwa Reuben informal slum settlements. About 20 kg of the waste was collected and contained food waste, vegetable waste and fruit waste, in equal proportions. Size reduction was achieved by manual chopping to about 1 cm size for pilot-scale test substrates whereas samples for laboratory-scale tests were blended using Ramton© domestic blender for 1 minute. Table 1 shows the characteristics of the UDDT-F and OMW that was used in the study. After collection the waste was refrigerated at 4 °C to minimise bioconversion of the samples prior to testing.

Inoculum

Inoculum for the AD experiments used in this study was obtained from an onsite fixed dome anaerobic digester within Kibera informal settlement, Kenya. The bio-centre was erected by Umande Trust, a non-governmental organisation (https://umande.org/) and managed in partnership with a community-based organisation, Kibera Kids Youth Organisation (KIDYOT). The inoculum upon collection was incubated for 1 week to methanise any organic matter before use.

Experimental setup

Laboratory-scale BMP test

BMP test experiments were performed to access methane production during anaerobic stabilisation of faecal waste. Three substrate ratios, based on our previous study (Riungu *et al.* 2018a), that investigated the effect of volatile fatty acids (VFAs) on pathogen inactivation were applied; UDDT-F:OMW ratios 1:0, 4:1 and 0:1. An inoculum to substrate ratio of 2:1 (Zeng *et al.* 2010) was used, maintaining approximately 1.5 g volatile solids (VS)/100 mL solution, based on initial VS concentration of inoculum and substrate.

Batch digestion experiments were conducted in triplicate using 100 mL glass serum vials (80 mL working volume). After adding the required amounts of substrate and inoculum in each serum vial, basic anaerobic medium (BAM) was added according to Angelidaki *et al.* (2009) (Table 2), in addition to 1 g/L sodium carbonate buffer. Hereafter, tap water was added to a volume of 80 mL. The vials were sealed with butyl rubber stoppers and flushed with argon gas for 30 seconds to purge out oxygen. The vials were incubated at 35(±1) °C for 30 days, with manual mixing. Triplicate blanks that contained inoculum and BAM were incubated in order to correct for gas production from the inoculum. Gas pressure in the digesters was measured regularly with a digital pressure meter model GMH 3150 (Greisinger, Germany) utilising a sensor model MSD 4 BAE with a resolution of 1 mbar.

Pilot-scale AD experiments

Pilot-scale substrate selection was based on a series of laboratory-scale batch-tests derived from previous experimental data (Riungu *et al.* 2018a) applying UDDT-F:OMW ratios of 4:1 and 1:0. In addition, research aimed at treating the highest possible substrate's TS concentration that can freely flow through the plug flow digester without the necessity of using pumps. As such, 12% TS was chosen as the highest substrate TS concentration with additional experiments at 10% TS for assessing the impact of lower TS concentrations on biogas production.

Table 1 | Characterisation of urine diverting dehydrating toilets waste and mixed organic market waste used in the study (Riungu *et al.* 2018a)

		UDDT-F		OMW	
		Value	**STDEV**	**Value**	**STDEV**
Total solids (TS)	(%)	24.5	3.8	17.9	1.6
Moisture content	(%)	75.5	3.8	80.7	4.1
Volatile solids (VS)	(% wgt)	20.1	3.5	16.9	4.4
Total organic carbon (TOC)	(g C/g TS)	64.4	7.7	54	4.3
Chemical oxygen demand $(COD)_{Total}$	(g COD/g TS)	195.3	5.9	139.6	10.1
Escherichia coli (*E. coli*)	(CFU/g TS)	1.7×10^9	5.3×10^8	2.7×10^5	7.4×10^4
Ascaris eggs		Not detected		Not detected	

Table 2 | Nutrients applied for BMP test

	Composition (g/L)	Dose (mL/L)		Composition (g/L)	Dose (mL/L)
Macronutrients					
NH_4Cl	170	2			
KH_2PO_4	37	2			
$CaCl_22H_2O$	8	2			
$MgSO_4.4H_2O$	9	2			
Trace elements and micronutrients					
$FeCl_3.4H_2O$	2	1	Resazurine	0.5	1
$ZnCl_2$	0.05	1	HCl (36%)	1 mL/L	1
H_3BO_3	0.05	1	EDTA	1	1
$CuCl_2.2H_2O$	0.03	1	$NiCl_2.6H_2O$	0.05	1
$MnCl_2.4H_2O$	0.5	1	$Na_2SeO_3.5H_2O$	0.1	1
$CoCl_2.6H_2O$	2	1	Yeast extract	0.1	1
$(NH_4)6Mo_7O_{24}.4H_2O$	0.09	1	$NaC_2H_3O_2 - 3H_2O$	1 g COD/L	1 g COD/L

Two sets of digesters were used, namely a one-stage digester (R_o) and a two-stage digester (R_{am}) comprising a hydrolysis/acidogenic digester (R_a) and a methanogenic digester (R_m).

Hydrolysis digester

The hydrolysis digesters (R_a) were fabricated from 30 L plastic containers, with a working volume of 20 L. These digesters were equipped with a cover, incorporated with two separate ports, i.e. a feeding port and a port fixed with a manual stirring mechanism, whereas the bottom of each digester was equipped with a discharge/effluent valve.

Plug flow digester

Six plug flow digesters (Figure 1) were constructed using 175 L tubular polyethylene bags, with polyethylene material thickness being 0.2 mm. The digesters had a liquid capacity of 145 L, with up to 30 L available for in-vessel biogas storage. The majority of biogas produced flowed by pressure to a 175 L biogas storage bag that was installed directly above each digester. In addition, three separate ports were incorporated onto each bag: inlet port (SP_1); sampling port (SP_2) at 0.7 m digester length; a gas discharge port at 1.4 m digester length; and effluent/discharge port (SP_3) at 2.1 m digester length. A total SRT of 29 days was maintained for the AD process.

Plug flow digester start-up and operation in one- and two-stage AD

Digesters were inoculated using the inoculum described above under 'Inoculum'. The six plug flow digesters D_1, D_2, D_3, D_4, D_5 and D_6, were divided into two groups, D_1-D_3-D_5 and D_2-D_4-D_6, referring to one-stage digestion of UDDT-F:OMW ratio 1:0 at 12% TS ($R_{o\text{-}1:0,12\%}$) and UDDT-F:OMW ratio 1:0 at 10% TS ($R_{o\text{-}1:0,10\%}$), respectively.

Figure 1 | Plug flow digester layout; digesters on the floor, biogas collection bags directly above; sampling points at different length of the digester are indicated as SP_1, SP_2 and SP_3, respectively.

Every morning, 5 L/day of the substrate was fed to the respective digesters. Stabilisation of the digesters was achieved after 6 weeks, and sample collection and analysis commenced and continued for a further 8 weeks.

The impact of co-digestion on biogas production and organic matter stabilisation was assessed by applying both one- and two-stage digesters, utilising a UDDT-F:OMW ratio of 4:1 at 12% TS, i.e. $R_{o\text{-}4:1,12\%}$ and $R_{am\text{-}4:1,12\%}$, respectively. In these experiments, the six plug flow digesters were also divided into two treatments groups, where digesters D_1-D_3-D_5 consisted of the two-stage $R_{am\text{-}4:1,12\%}$ digesters and digesters D_2-D_4-D_6 comprised the one-stage $R_{o\text{-}4:1,12\%}$ digesters. Every morning, 5 L of feed substrate was fed into the one- and two-stage digesters, with feed substrate being prepared as follows: (1) One-stage: freshly prepared UDDT-F:OMW ratio of 4:1 at 12% TS concentration, (2) Two-stage: Hydrolysis/acidogenic (R_a) digester effluent acted as influent to the methanogenic digesters (R_m). The pH of R_a effluent (4.9 ± 0.1) was adjusted by titration using two-stage (R_{am}) digester effluent to a range of 5.8–6.2 prior to feeding it to the R_m digesters. For all digesters, stabilisation of biogas production was achieved after two months when data collection commenced. Finally, the concentration of the feed into $R_{o\text{-}4:1,12\%}$ was reduced to 10% TS.

Samples from experiments were taken on a weekly basis for analysis of TS and volatile solids (VS), whereas biogas and methane analysis was carried out on a daily basis over the entire experimental period.

Analytical procedures

Biogas production in laboratory-scale BMP vials was determined by measuring the pressure increase in the headspace volume (20 mL) using a digital pressure meter model GMH 3150 (Greisinger, Germany) utilising a sensor model MSD 4 BAE with a resolution of 1 mbar. The volumetric biogas production was calculated from the assessed pressure increase and expressed under standard temperature and pressure (STP, 0 °C and 760 mm Hg) according to the following equation (Pabon Pereira et al. 2012):

$$V_{Biogas} = \frac{P.V_h V_{mol}}{R.T} \tag{1}$$

where P is biogas pressure in the vial (kPa); V_h is digester headspace volume (L); V_{mol} is molar gas volume at 308 K (L/mol); R is the universal gas constant (8.31 kPa L/mol K) and T is temperature (K).

The net gas production for calculating the BMP values was obtained by subtracting the gas production of the blank samples.

Biogas flow measurements in the pilot-scale digesters were performed using American Meter Company gas flow meters (Model AC-250) with IMAC Systems pulse digital counters and a vacuum pump.

Determination of methane content in biogas in laboratory- and pilot-scale experiments was performed by liquid displacement method. Herein, a known amount of biogas was passed through a 5% sodium hydroxide solution to strip CO_2. Under laboratory-scale BMP test, methane measurement was carried out twice a week while in pilot-scale test, methane measurement was done once a day. In this approach the quantity of H_2S in the biogas is considered negligible.

The percentage methane fraction in biogas was obtained by:

$$\%CH_4 = \frac{\text{Volume of displaced NaOH solution}}{\text{Volume of gas injected}} * 100 \tag{2}$$

Methane production was then calculated by multiplying the mean corrected biogas volume produced in a specified time lapse by the assessed average percentage methane content in the biogas, whereas methane yields were obtained by dividing the total methane volume produced in the specified time lapse by the weight of the substrate (VS_{added} (in g)) fed to the plug flow digesters in the same time lapse, according to the following equation:

$$V_{CH_4} = \%_{CH_4} \frac{V' \text{ biogas} - V'' \text{biogas}}{VS} \tag{3}$$

where % CH_4: fraction of methane in biogas; V' biogas is the volume of biogas produced on the substrate; V'' biogas is the volume of biogas produced by the blank; and VS is volatile solids added (g).

TS and volatile solids (VS) analysis were conducted according to the gravimetric method (SM-2540D and

SM-2540E), as outlined in *Standard Methods for the Examination of Water and Wastewater* (APHA 1995).

Data analysis

Bivariate Pearson's correlation test was used to assess trends in methane production from individual digesters within a given experiment. From each of the three trials, the data obtained was analysed by computing the averages, standard deviations and standard errors. Results obtained were presented either in table or figure form.

RESULTS AND DISCUSSION

Methane production in batch-scale BMP tests

Figure 2 shows cumulative methane produced against time for UDDT-F:OMW ratios 1:0, 4:1 and 0:1. Highest methane production was recorded within the first 10 days of the experiment, with UDDT-F:OMW ratio 0:1 attaining 45.8 mL CH_4/g VS added/day (Figure 2) whereas UDDT-F:OMW ratios 1:0 and 4:1 depicted 27.3 and 17.1 mL CH_4/g VS added/day respectively. After the 10th day, a decline in methane production was observed up to the 30th day of the experiment.

Overall, 271 ± 13, 315 ± 26 and 521 ± 36 mL CH_4/g VS_{added} was recorded from UDDT-F:OMW ratios 1:0, 4:1 and 0:1 respectively (Figure 2). An average of about 0.26–0.30 L CH_4/g VS_{added} has been reported in batch-scale BMP assays of black water (Rajagopal *et al.* 2013), and about 250 mL CH_4/g VS_{added} in AD of human faecal material (faeces + urine) (Fagbohungbe *et al.* 2015). The findings showed an increasing trend in biogas production with the increase in OMW fraction within the feed substrate, which is congruent to the observed higher VFA build-up at increasing OMW fractions in our previous work (Riungu *et al.* 2018a). The produced VFA was subsequently converted to biogas. In practical situations where biogas generation is the main driver for implementing AD, the use of OMW as sole substrate may lead to excessive VFA build-up and subsequent system acidification (Angeriz-Campoy *et al.* 2015; Riungu *et al.* 2018a). In our previous work, pH levels declined to below 4 at UDDT-F:OMW ratios lower than 1:2, inhibiting methanogenic activity. In general, OMW is carbohydrate rich, has a high C/N ratio and is easily hydrolysable (Gómez *et al.* 2006; Lim *et al.* 2008), in addition to containing appreciable amounts of fats that are easily hydrolysable to long chain fatty acids (Silva *et al.* 2014; Angeriz-Campoy *et al.* 2015). As such, in co-digestion of OMW and UDDT-F, both substrates complement each other: UDDT-F is characterised by a low carbon to nitrogen ratio (Mata-Alvarez *et al.* 2011; Fonoll *et al.* 2015) and low methane production (Rajagopal *et al.* 2013), it provides adequate micro/macro nutrients, alkalinity and moisture content (Silvestre *et al.* 2015).

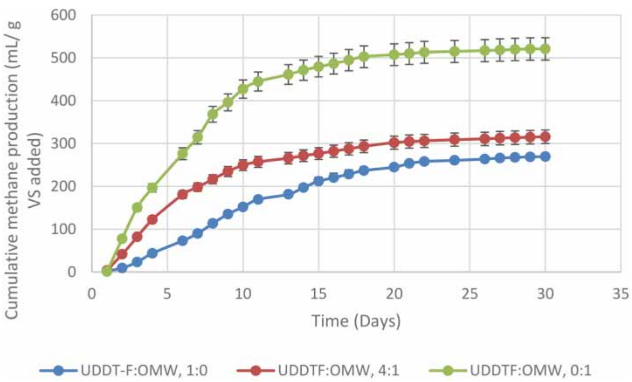

Figure 2 | Cumulative methane production against time in anaerobic digestion of UDDT-F ratios 1:0, 4:1 and 0:1.

Pilot-scale experiments

Evaluation of methane production

The experiments evaluated the impact of digester configuration, co-digestion and substrate concentration on the accumulating methane production during an 8-week time period. All digesters showed a linear increase in accumulating methane with time (Figure 3). Overall, the obtained trend in accumulated methane production per g VS added was in the order: $R_{am\text{-}4:1,12\%} > R_{am\text{-}4:1,10\%} > R_{o\text{-}1:0,12\%} > R_{o\text{-}1:0,12\%} > R_{o\text{-}1:0,10\%}$, with minimal differences between the co-digesting experiments (Figure 4). Results from bivariate Pearson's correlation test performed on triplicate samples within each experiment showed high and significant correlation in methane production within a particular experiment, all being within the range of

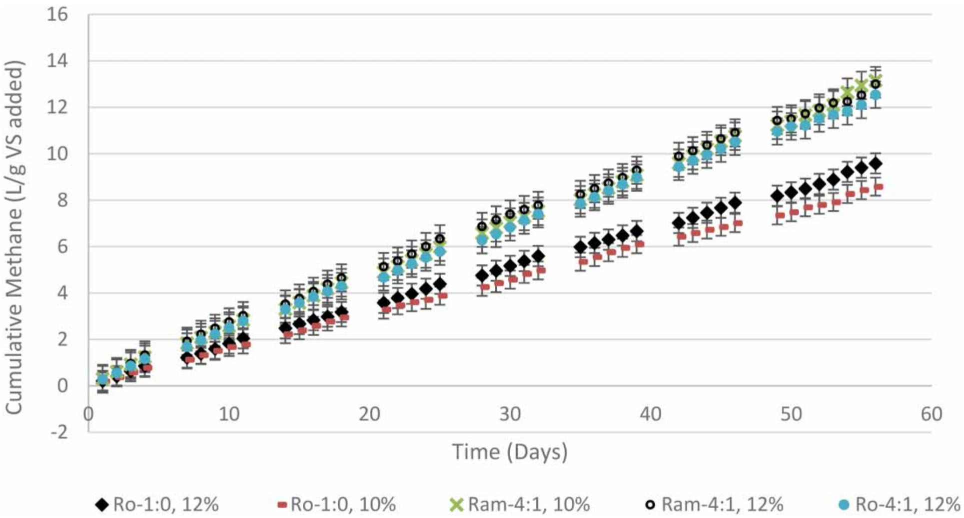

Figure 3 | Cumulative methane produced (L/g VS added) against time (days).

r = 0.474**–0.840** (**correlation is significant at the 0.01 level (2-tailed)), indicating good digester progress throughout the experimental period.

The effect of digester configuration was gauged by applying a UDDT:OMW ratio of 4:1 at 12% TS in a one-stage ($R_{o\text{-}4:1,12\%}$) and two-stage digester ($R_{am\text{-}4:1,12\%}$). Methane production in $R_{o\text{-}4:1,12\%}$ and $R_{am\text{-}4:1,12\%}$ digester was comparable with corresponding values being 314 ± 15 and 325 ± 12 mL CH_4/g VS added (Figure 4), respectively.

However, average biogas production in $R_{am\text{-}4:1,12\%}$ was 571 ± 25 mL CH_4/g VS added and was about 12% higher than in the $R_{o\text{-}4:1,12\%}$ system which is significantly more than the slight difference in methane production, i.e. 3–4%.

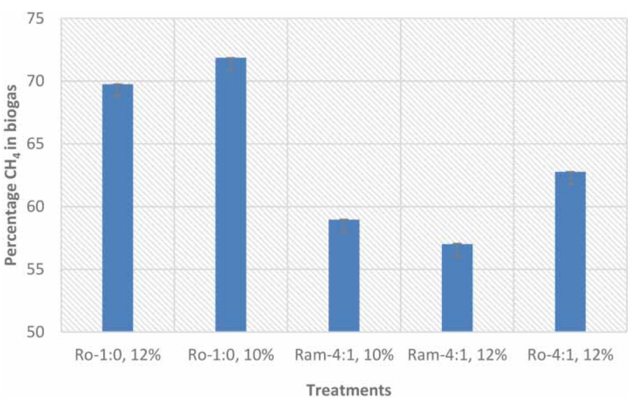

Figure 4 | Percentage methane content in biogas during anaerobic stabilisation of UDDT-F for; two-stage digester ($R_{am\text{-}4:1,12\%}$ and $R_{am\text{-}4:1,10\%}$) and one-stage digester ($R_{O\text{-}4:1,12\%}$, $R_{O\text{-}1:0,12\%}$ and $R_{O\text{-}1:0,12\%}$).

The small difference in methane production may be attributed to enhanced waste solubilisation in the two-stage digester, as reported in our previous study (Riungu *et al.* 2018b) and in agreement with related studies (Zuo *et al.* 2014; De Gioannis *et al.* 2017; Gaby *et al.* 2017). On the other hand, the observed higher biogas production in the two-stage digester likely can be ascribed to increased CO_2 dissolution, resulting from mixing the bicarbonate-rich methanogenic effluent for neutralisation purposes with the low pH (4.9) influent coming from the pre-acidification stage. The latter also explains the lower CH_4 content in the produced biogas in the gas bags of the two-stage digester and the higher pH in the effluent (Table 3). In the two-stage set-up, part of the produced acidity is already lost as CO_2 in the pre-acidification step that was open to air, leading to a higher overall alkalinity of the methanogenic effluent compared to the one-stage process.

In the two-stage digestion set-up with digestate recycling, the chances for possible acidification in the front part of the methanogenic plug flow digester is reduced. An active methanogenic activity in the front part of $R_{am\text{-}4:1,12\%}$ digester as indicated by a decline in total volatile acids (TVFA) concentrations between SP_1 and SP_3, and their subsequent conversion to biogas (Table 3) was observed. As mentioned before, the stabilised methanogenic conditions in the early stages of the plug flow digester of the two-stage set-up were achieved by digestate or effluent recycling that re-introduces active methanogenic biomass

Table 3 | Variation in VFA and pH along the digester length (adopted from Riungu *et al.* 2018b)

	Digester	Parameter	SP_1	SP_2	SP_3
Co-digestion UDDT-F:OMW ratio 4:1	$R_{m-4:1,12\%}$	TVFA (mg/L)	15,685 ± 1,772	10,526 ± 844	1,575 ± 607
		ND-VFA (mg/L)	800 ± 112	286 ± 68	1.7 ± 0.2
		ND-VFA (%)	5.1 ± 0.6	2.7 ± 0.6	0.1
		pH	6.4 ± 0.1	6.4 ± 0.1	7.8 ± 0.1
	$R_{m-4:1,10\%}$	TVFA (mg/L)	12,347 ± 887	8,702 ± 72	1,744 ± 101
		ND-VFA (mg/L)	660 ± 311	281 ± 49	1.6 ± 0.3
		ND-VFA (%)	3.5 ± 2	3.2 ± 0.6	0.1
		pH	6.3 ± 0.1	6.2 ± 0.1	7.8 ± 0.1
	$R_{o-4:1,12\%}$	TVFA (mg/L)	3,844 ± 679	12,121 ± 1,153	2,629 ± 326
		ND-VFA (mg/L)	599.4 ± 150	2,379 ± 409	5 ± 1.2
		ND-VFA (%)	15.8 ± 3.4	19.6 ± 2.8	0.2
		pH	5.4 ± 0.1	5.4 ± 0.1	7.5 ± 0.1

upfront (Cavinato *et al.* 2011). However, the $R_{o\text{-}4:1,12\%}$ digester showed an increasing trend in total volatile acids (TVFA), and non-dissociated volatile acids (ND-VFA) build-up between SP_1 and SP_2, resulting in an acidic pH 5.4 thus indicating predominating acidogenesis in the first part of the plug flow digester (Table 3). In this digester, highest methanogenic activity was observed between SP_2 and SP_3, where high reduction in TVFA indicated their subsequent conversion to biogas.

The impact of co-digestion on methane production in the one-stage digestion process was assessed by applying a UDDT:OMW ratio of 4:1, at 12% TS ($R_{o\text{-}4:1,12\%}$) and a UDDT:OMW ratio of 1:0, at 12% TS ($R_{o\text{-}1:0,12\%}$). Methane production in $R_{o\text{-}4:1,12\%}$ and $R_{o\text{-}1:0,12\%}$ digester system was 314 ± 15 and 228 ± 19 l CH_4/g VS added (Figure 5)

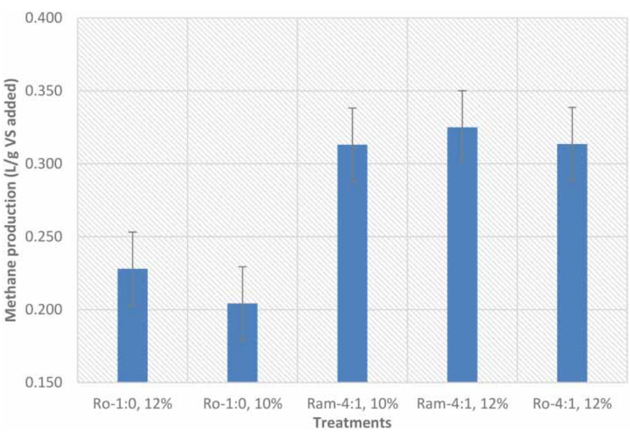

Figure 5 | Methane production during anaerobic stabilisation of stabilisation of UDDT-F for; two-stage digester ($R_{am\text{-}4:1,12\%}$ and $R_{am\text{-}4:1,10\%}$) and one-stage digester ($R_{o\text{-}4:1,12\%}$, $R_{o\text{-}1:0,12\%}$ and $R_{o\text{-}1:0,10\%}$).

respectively, representing a 37% increase when OMW was added. The corresponding percentage methane content in biogas in $R_{o\text{-}4:1,12\%}$ and $R_{o\text{-}1:0,12\%}$ digester system was 62.8 ± 2 and 70.0 ± 4.5% respectively. The lower CH_4 content in the biogas of the co-digester comes from the OMW fraction of the feed substrate which is generally characterised by carbohydrate-rich organic matter with a somewhat higher oxidation state than the UDDT-F, which agrees with the lower COD/TOC ratio for OMW as presented in Table 1. Also, the higher methane production (in L CH_4/g VS added) in $R_{o\text{-}4:1,12\%}$ is attributable to the highly digestible OMW fraction, reflected by the high TVFA build-up attained during the digestion process (Table 2). Intrinsically, during co-digestion, hydrolysis of OMW enhances TVFA build-up in the digestion medium (Zhang *et al.* 2005; Zhang *et al.* 2008; Riungu *et al.* 2018a), which is subsequently converted to biogas but may lead to subsequent system acidification (Angeriz-Campoy *et al.* 2015) if used as sole substrate.

The potential impact of substrate concentration on methane production was investigated applying two substrate concentrations, i.e. 12 and 10% TS. These concentrations were applied in both the one-stage and two-stage plug flow digesters, at UDDT-F:OMW ratios of 1:0 and 4:1 respectively. Using both digester systems, slightly higher methane production was observed at 12% TS than 10% TS. The two-stage digesters $R_{am\text{-}4:1,12\%}$ produced 325 ± 12 mL CH_4/g VS_{added} whereas the corresponding value in $R_{am\text{-}4:1,10\%}$ was 313 ± 17 mL CH_4/g VS_{added}. Similarly, in the one-stage digester, $R_{o\text{-}1:0,12\%}$ and $R_{o\text{-}1:0,10\%}$ the observed methane production was 228 ± 19 mL CH_4/g VS and 204 ± 22 mL CH_4/g VS_{added} respectively. The percentage methane in the biogas of $R_{am\text{-}4:1,12\%}$ and $R_{am\text{-}4:1,10\%}$ digesters at 10 and 12% TS were 57 ± 8 and 59 ± 4%, respectively (Figure 3). Corresponding values in $R_{o\text{-}1:0,12\%}$ and $R_{o\text{-}1:0,10\%}$ digesters being 70 ± 2 and 71 ± 8% respectively. Furthermore, all digesters showed stable digestion performance with effluent pH in the one-stage digesters a bit lower compared to the two-stage digesters, i.e. 7.3–7.7 and 7.6–8.1, respectively. The average pH in the methanogenic stage is considered optimal for the methanogenic biomass, i.e. 7.5–8.1.

AD application of UDDT-F management in informal slum settlements

This study is part of a wide research seeking to enhance biogas production and pathogen inactivation from UDDT-F in high-density informal slum settlements. The key objective of the research was to maximise the amounts of UDDT-F that can be treated, while producing biogas and stabilised digestate that can be used for agricultural applications. The findings obtained in this research demonstrated the technical feasibility of AD technology in UDDT-F management. Moreover, in addition to efficient management of the waste, the produced biogas has a wide range of applications.

The possibilities of reactor failure are apparent during co-digestion, especially at increased OMW fraction due to reactor acidification. The UDDT-F:OMW ratio 4:1 adopted in this study was based on recommendations from our previous study (Riungu *et al.* 2018a). Increasing the OMW fraction in the feed substrate leads to rapid acidification thereby lowering the pH and increasing the ND-VFA concentration that has a toxic effect not only to pathogens but all anaerobic bacterial population, thus process failure. As such, precaution should be taken to ensure application of optimal UDDT-F:OMW ratios during co-digestion.

Results showed that co-digestion in the proposed plug-flow digester produced a low pathogen content–digestate, i.e. $<1*10^3$ CFU/100 mL (Riungu *et al.* 2018b)) and a biogas stream that can be used as an alternative fuel source for slum residents, delivering about 6,500 MJ/month for a bio-centre with a user load of 500 persons/day. The system presents a cost-effective solution for the many slum areas in sub-Saharan Africa: the plug-flow reactor can be assembled with locally available materials and the high population density assures a constant supply of raw materials, whereas the prevailing high temperatures ensure the system's zero energy operating requirements.

CONCLUSIONS

Experiments were conducted to investigate the biochemical energy recovery during digestion and co-digestion of faecal matter collected from urine diverting dehydrating toilet faeces (UDDT-F) and mixed OMW under laboratory- and pilot-scale conditions. Laboratory-scale BMP tests showed a positive correlation between methane production and increasing OMW fraction in the feed substrate.

Under pilot-scale conditions, comparable methane production was observed in one-stage ($R_{o\text{-}4:1,12\%}$) (314 ± 15 mL CH_4/g VS added) and two-stage ($R_{am\text{-}4:1,12\%}$) (325 ± 12 mL CH_4/g VS added) digesters, when applying 12% TS slurry concentration. However, biogas production in $R_{am\text{-}4:1,12\%}$ digester (571 ± 25 mL CH_4/g VS added) was about 12% higher than in the $R_{o\text{-}4:1,12\%}$, significantly more than the slight difference in methane production, i.e. 3–4%. The increased methane and biogas production was attributed to enhanced waste solubilisation and increased CO_2 dissolution, resulting from mixing the bicarbonate-rich methanogenic effluent for neutralisation purposes with the low pH (4.9) influent coming from the pre-acidification stage. Moreover, compared to the one-stage reactor, higher process stability was observed in the first parts of the two-stage plug flow digester, characterised by lower VFA concentrations. The observed high VFA concentrations and acidic pH (5.4) in the first parts of one-stage digester indicate low process stability, particularly with increased OMW fractions in the feed substrate.

Within the wide research, overall findings have shown the potential application of two-stage AD technology in addressing the human waste menace, especially in high density slum settlements. The proposed system can be applied at either small or large scale, depending on available space. The treatment system has almost zero energy requirements when implemented in warm areas where optimal mesophilic temperatures can be reached without heating.

ACKNOWLEDGEMENTS

This research is funded by the Bill & Melinda Gates Foundation under the framework of SaniUp project (Stimulating local Innovation on Sanitation for the Urban Poor in Sub-Saharan Africa and South-East Asia) (OPP1029019). The authors would like to thank Ani Vabharneni, Sanergy Kenya, and DVC-ARS, Meru University, Kenya for their valuable support during this study.

REFERENCES

Abbasi, T., Tauseef, S. M. & Abbasi, S. A. 2012 Anaerobic digestion for global warming control and energy generation – an overview. *Renew. Sust. Energy Rev.* **16**, 3228–3242.

Angelidaki, I., Alves, M. & Bolzonella, D. 2009 Defining the biomethane potential (BMP) of solid organic wastes and energy crops: a proposed protocol for batch assays. *Water Sci. Technol.* **59**, 927–934.

Angeriz-Campoy, R., Álvarez-Gallego, C. J. & Romero-García, L. I. 2015 Thermophilic anaerobic co-digestion of organic fraction of municipal solid waste (OFMSW) with food waste (FW): enhancement of bio-hydrogen production. *Bioresour. Technol.* **194**, 291–296.

APHA 1995 *Standard Methods for the Examination of Water and Wastewater*, 19th edn. American Public Health Association, Washington, DC, USA.

Austin, L. M. & Cloete, T. E. 2008 Safety aspects of handling and using fecal material from urine-diversion toilets – a field investigation. *Water Environ. Res.* **80** (4), 308–315.

Avery, L. M., Anchang, K. Y., Tumwesige, V., Strachan, N. & Goude, P. J. 2014 Potential for pathogen reduction in anaerobic digestion and biogas generation in Sub-Saharan Africa. *Biomass Bioenergy* **70**, 112–124.

Berndes, G., Hoogwijk, M. & van den Broek, R. 2003 The contribution of biomass in the future global energy supply: a review of 17 studies. *Biomass Bioenergy* **25** (1e), 28.

Cavinato, C., Bolzonella, D., Fatone, F., Cecchi, F. & Pavan, P. 2011 Optimization of two-phase thermophilic anaerobic digestion of biowaste for hydrogen and methane production through reject water recirculation. *Bioresour. Technol.* **102** (18), 8605–8611.

Chaggu, E. J. 2004 *Sustainable Environmental Protection Using Modified Pit-Latrines*. PhD Thesis, Wageningen University, The Netherlands.

Chen, Y., Fu, B., Wang, Y., Jiang, Q. & Liu, H. 2012 Reactor performance and bacterial pathogen removal in response to sludge retention time in a mesophilic anaerobic digester treating sewage sludge. *Bioresour. Technol.* **106** (Supplement C), 20–26.

De Gioannis, G., Muntoni, A., Polettini, A., Pomi, R. & Spiga, D. 2017 Energy recovery from one- and two-stage anaerobic digestion of food waste. *Waste Manage.* **68**, 595–602.

Fagbohungbe, M. O., Herbert, B. M. J., Li, H., Ricketts, L. & Semple, K. T. 2015 The effect of substrate to inoculum ratios on the anaerobic digestion of human faecal material. *Environ. Technol. Innov.* **3**, 121–129.

Feachem, R. G., Bradley, D. J., Garelick, H. & Mara, D. 1983 *Sanitation and Disease Health Aspects of Excreta and Wastewater Management*. World Bank Studies in Water Supply and Sanitation, No. 3. John Wiley & Sons, New York, NY. Available from: http://documents.worldbank.org/curated/en/704041468740420118/Sanitation-and-disease-health-aspects-of-excreta-and-wastewater-management.

Fonoll, X., Astals, S., Dosta, J. & Mata-Alvarez, J. 2015 Anaerobic co-digestion of sewage sludge and fruit wastes: evaluation of the transitory states when the co-substrate is changed. *Chem. Eng. J.* **262**, 1268–1274.

Gaby, J. C., Zamanzadeh, M. & Horn, S. J. 2017 The effect of temperature and retention time on methane production and microbial community composition in staged anaerobic digesters fed with food waste. *Biotechnol. Biofuels* **10** (1), 302.

Gómez, X., Morán, A., Cuetos, M. J. & Sánchez, M. E. 2006 The production of hydrogen by dark fermentation of municipal solid wastes and slaughterhouse waste: a two-phase process. *J. Power Sources* **157** (2), 727–732.

Horan, N. J., Fletcher, L., Betmal, S. M., Wilks, S. A. & Keevil, C. W. 2004 Die-off of enteric bacterial pathogens during mesophilic anaerobic digestion. *Water Res.* **38** (5), 1113–1120.

Katukiza, A. Y., Ronteltap, M., Niwagaba, C. B., Foppen, J. W. A., Kansiime, F. & Lens, P. N. L. 2012 Sustainable sanitation technology options for urban slums. *Biotechnol. Adv.* **30** (5), 964–978.

Kunte, D. P., Yeole, T. Y. & Ranade, D. R. 2000 Inactivation of Vibrio cholerae during anaerobic digestion of human night soil. *Bioresour. Technol.* **75** (2), 149–151.

Lim, S.-J., Kim, B. J., Jeong, C.-M., Choi, J.-D.-R., Ahn, Y. H. & Chang, H. N. 2008 Anaerobic organic acid production of food waste in once-a-day feeding and drawing-off bioreactor. *Bioresour. Technol.* **99** (16), 7866–7874.

Martín-González, L., Colturato, L. F., Font, X. & Vicent, T. 2010 Anaerobic co-digestion of the organic fraction of municipal solid waste with FOG waste from a sewage treatment plant: recovering a wasted methane potential and enhancing the biogas yield. *Waste Manage.* **30** (10), 1854–1859.

Massé, D., Gilbert, Y. & Topp, E. 2011 Pathogen removal in farm-scale psychrophilic anaerobic digesters processing swine manure. *Bioresour. Technol.* **102** (2), 641–646.

Mata-Alvarez, J., Dosta, J., Macé, S. & Astals, S. 2011 Codigestion of solid wastes: a review of its uses and perspectives including modeling. *Crit. Rev. Biotechnol.* **31**, 99–111.

Niwagaba, C., Kulabako, R. N., Mugala, P. & Jönsson, H. 2009a Comparing microbial die-off in separately collected faeces with ash and sawdust additives. *Waste Manage.* **29** (7), 2214–2219.

Niwagaba, C., Nalubega, M., Vinnerås, B., Sundberg, C. & Jönsson, H. 2009b Bench-scale composting of source-separated human faeces for sanitation. *Waste Manage.* **29** (2), 585–589.

Pabon Pereira, C. P., Castanares, G. & van Lier, J. B. 2012 An OxiTop((R)) protocol for screening plant material for its biochemical methane potential (BMP). *Water Sci. Technol.* **66** (7), 1416–1423.

Pabón-Pereira, C. P., de Vries, J. W., Slingerland, M. A., Zeeman, G. & van Lier, J. B. 2014 Impact of crop-manure ratios on energy production and fertilizing characteristics of liquid and solid digestate during co-digestion. *Environ. Technol.* **35** (19), 2427–2434.

Park, K. Y., Jang, H. M., Park, M.-R., Lee, K., Kim, D. & Kim, Y. M. 2016 Combination of different substrates to improve anaerobic digestion of sewage sludge in a wastewater treatment plant. *Int. Biodeter. Biodegrad.* **109**, 73–77.

Rajagopal, R., Lim, J. W., Mao, Y., Chen, C.-L. & Wang, J.-Y. 2013 Anaerobic co-digestion of source segregated brown water (feces-without-urine) and food waste: for Singapore context. *Sci. Total Environ.* **443**, 877–886.

Riungu, J., Ronteltap, M. & van Lier, J. B. 2018a Build-up and impact of volatile fatty acids on *E. coli* and A. lumbricoides during co-digestion of urine diverting dehydrating toilet (UDDT-F) faeces. *J. Environ. Manage.* **215**, 22–31.

Riungu, J., Ronteltap, M. & van Lier, J. B. 2018b Volatile fatty acids (VFA) build-up and its effect on *E. coli* inactivation during excreta stabilisation in single-stage and two-stage systems. *J. Water Sanit. Hyg. Dev.* **8** (2), 257–267.

Schouten, M. A. C. & Mathenge, R. W. 2010 Communal sanitation alternatives for slums: a case study of Kibera. *Kenya. Phys. Chemistry Earth A/B/C* **35** (13–14), 815–822.

Silva, S. A., Cavaleiro, A. J., Pereira, M. A., Stams, A. J. M., Alves, M. M. & Sousa, D. Z. 2014 Long-term acclimation of anaerobic sludges for high-rate methanogenesis from LCFA. *Biomass Bioenergy* **67**, 297–303.

Silvestre, G., Bonmatí, A. & Fernández, B. 2015 Optimisation of sewage sludge anaerobic digestion through co-digestion with OFMSW: effect of collection system and particle size. *Waste Manage.* **43**, 137–143.

Strande, L., Ronteltap, M. & Brdjanovic, D. 2014 *Faecal Sludge Management, Systems Approach for Implementation and Operation*. IWA Publishing, London.

Van Lier, J. B., Mahmoud, N. & Zeeman, G. 2008 *Biological Wastewater Treatment: Principles, Modelling and Design. Chapter 16: Anaerobic Waste Water Treatment*. IWA Publishing, London.

Vinnerås, B. 2007 Comparison of composting, storage and urea treatment for sanitising of faecal matter and manure. *Bioresour. Technol.* **98** (17), 3317–3321.

Zeng, S., Yuan, X., Shi, X. & Qiu, Y. 2010 Effect of inoculum/substrate ratio on methane yield and orthophosphate release from anaerobic digestion of *Microcystis* spp. *J. Hazard. Mater.* **178** (1), 89–93.

Zhang, B., Zhang, L. L., Zhang, S. C., Shi, H. Z. & Cai, W. M. 2005 The influence of pH on hydrolysis and acidogenesis of kitchen wastes in two-phase anaerobic digestion. *Environ. Technol.* **3**, 329–339.

Zhang, B., He, P., Lü, F. & Shao, L. 2008 Enhancement of anaerobic biodegradability of flower stem wastes with vegetable wastes by co-hydrolysis. *J. Environ. Sci.* **20** (3), 297–303.

Zuo, Z., Wu, S., Zhang, W. & Dong, R. 2014 Performance of two-stage vegetable waste anaerobic digestion depending on varying recirculation rates. *Bioresour. Technol.* **162**, 266–272.

First received 18 June 2018; accepted in revised form 5 December 2018. Available online 20 March 2019