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Anaerobic digestion of undiluted simulant human excreta for sanitation and energy recovery in less-developed countries

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ABSTRACT

Improving access to sanitation is one of the most effective means to improve public health. Anaerobic digestion of high-strength undiluted human simulant excreta was investigated in laboratory systems. The focus was on demonstrating the suitability of using simple unmixed anaerobic digesters for the treatment of a simulant high-strength undiluted human excreta and to quantify the effects of high ammonia concentration on the biogas yield. A maximum biogas yield of 0.44 $NL_{biogas}\ g^{-1}{}_{COD}$ was obtained in batch experiments, while yields of 0.38 and 0.24 $NL_{biogas}\ g^{-1}{}_{COD}$ were obtained at 5 and 8 g total ammonia nitrogen (TAN) L^{-1}, respectively. Using an inoculum acclimated to high ammonia concentrations was critical to successful biogas production at these high TAN concentrations. Stable long-term anaerobic digestion of simulant human excreta at ammonia concentrations ranging from 5.20 to 7.15 g-N L^{-1} was obtained in a scaled-down mimic of a low cost floating dome anaerobic digester. Overall, the results demonstrate that anaerobic digestion of undiluted human simulant excreta in simple unmixed digesters is feasible and yields biogas, which is a valuable commodity. When combined with proper hygienization of its effluent, anaerobic digestion could contribute to effective sanitation in developing countries with limited water availability.

Acronyms–Notation

AD	anaerobic digestion
AI	acclimated inoculum
COD	chemical oxygen demand (t, diss, ss subscripts refer to total, dissolved or suspended, respectively)
dw	dry weight
FA	free ammonia
HRT	hydraulic retention time
NAI	non-acclimated inoculum
NL	normal liter (volume of gas at 273 K and 1 atm)
OLR	organic loading rate
RE	removal efficiency
STP	standard temperature and pressure
TAN	total ammonia nitrogen
TS	total solid
VFA	volatile fatty acids
VS	volatile solid

Introduction

Improving global access to clean drinking water and safe sanitation is one of the least expensive and most effective means to improve public health and save lives (Montgomery and Elimelech, 2007). In 2014, an estimated 2.5 billion people were still without improved sanitation, of which about 1 billion people practiced open defecation (WHO-UNICEF, 2014). The United Nations World Summit on Sustainable Development, held in Johannesburg, South Africa in 2002, articulated a number of targets for the coming decade, among these targets was to “halve by the year 2015, the proportion of people who do not have access to basic sanitation” (Dellström, 2005). Sanitation coverage by region shows marked differences. While in developed countries the coverage rate is >95%, many countries are not on track in meeting the ≥75% coverage Millennium Development Goals for sanitation. Sub-Saharan Africa, Oceania and Southern Asia are the three regions with the lowest sanitation coverage (30%, 35% and 42%, respectively) (WHO-UNICEF, 2014).

The impacts of poor sanitation are staggering. Fecal–oral contamination is an underlying factor in more than 50% of child deaths in the developing world. Every year, food and water tainted with fecal matter cause up to 2.5 billion cases of diarrhea among children, resulting in

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600,000 child deaths (BMGF, 2011). Furthermore, the WEHAB estimated that in China, India and Indonesia, twice as many people are dying from diarrheal diseases as from HIV/AIDS (WEHAB, 2002).

One of the major challenges with sanitation is developing and implementing innovative, user-friendly, low-cost systems. The centralized sewer-based collection and treatment systems existing in developed nations are too costly, too complex and use too much energy to implement in poor and less-developed countries (Lalander et al., 2013; Mara, 2013). Even in developed countries, the connection of dispersed human settlements such as remote houses, summerhouses, farms and some recreation facilities to sewerage systems is often too costly. Definitely, decentralized wastewater management is inevitable for comprehensive wastewater treatment and environmental protection worldwide. Decentralized sanitation technologies have the potential to convert urine and feces to safe end-products with fertilizing value for agricultural purposes (Dellström, 2005; Mara, 2013). Nitrogen and phosphorous have the greatest value in this context, while the organic matter offers possible energy recovery potential. The amount of feces and urine excreted daily by individuals varies considerably depending on water consumption, climate, diet and occupation. While the wet mass of feces excreted daily ranges between 70 and 520 g per person per day ($g\ p^{-1}\ d^{-1}$), an amount of 350–400 $g\ p^{-1}\ d^{-1}$ is generally considered as a reasonable average (Torondel, 2010; Wignarajah et al., 2006; Franceys et al., 1992; Fry, 1973). Similarly, the urine volume produced daily ranges between 0.6 and 1.1 $L\ p^{-1}\ d^{-1}$, and an average of 1 $L\ p^{-1}\ d^{-1}$ is suggested (Putnam, 1971; Franceys et al., 1992). These average excreta values correspond to a total of about 70–80 $g_{dry}\ p^{-1}\ d^{-1}$ 1 or about 100–110 g chemical oxygen demand (COD) $p^{-1}\ d^{-1}$, almost all of it coming from the feces, a total of 7–10 g-N $p^{-1}\ d^{-1}$ (with 80–90% of the nitrogen coming from the urine) and about 1 g-P $p^{-1}\ d^{-1}$.

Anaerobic digestion (AD) is a well-established process in which bacteria convert organic wastes to a methane and CO_2 gas mixture (generally about 60% methane and 40% CO_2) called biogas. This is the process occurring naturally in septic tanks, although in that case, the methane is released to the environment. Methane emissions are a lost opportunity and an environmental liability: methane is a valuable source of energy (about 36 $kJ\ L^{-1}$ for methane at STP) and is a greenhouse gas generally agreed to be about 25 times more potent than CO_2 (on a mass basis) over a 100-year time frame.

There is very little reliable data on AD of undiluted human excreta. Snell (1943) published the first study on AD of human excreta: 0.5 $m^3_{biogas}\ kg^{-1}_{VS}$ was produced during the anaerobic digestion of human feces. However, when feces were mixed with urine, the anaerobic digestion process was completely inhibited (Snell, 1943). Park et al. (2001) reported a biogas production of up to 0.21 $m^3_{biogas}\ kg^{-1}_{COD}$ (or roughly 0.30 $m^3_{biogas}\ kg^{-1}_{VS}$) using an anaerobic sequencing batch reactor (ASBR) fed night soil and working at an organic loading rate (OLR) of 3.1 $kg_{COD}\ m^{-3}_{reactor}\ day^{-1}$, a temperature of 35 °C and a hydraulic retention time (HRT) of 10 days. They found a large increase in biogas production after implementing a thickening scheme, which allowed to concentrate solids in their bioreactor. Meher et al. (1994) reported a biogas production of 0.16 $m^3_{biogas}\ kg^{-1}_{VS}$ for AD of slightly diluted human waste (i.e., water consumption of 2.5 $L\ p^{-1}\ d^{-1}$) at psycrophilic temperatures (15 ± 1 °C) using a fixed dome anaerobic digester designed for a HRT of 30 days. Recently, Rajagopal et al. (2014) studied the co-digestion of brown water and food waste. They specifically separated feces from urine to increase the hydrolytic and acidogenic potential of co-digestion of food waste and feces. Additionally, co-digestion of excreta with other organics improves process efficiencies that are inhibited by excreta characteristics as seen in a similar study (Panyadee et al., 2013).

There is more information about treatment performance in septic tanks (Luostarinen et al., 2007; Canter and Knox, 1985) but usually the feedstock characteristics are very different compared to high-strength undiluted human excreta. Moreover septic tanks studies are generally focused on the removal of chemical oxygen demand (COD) and little or no information is given about methane or biogas production.

The main objective of the present study was to demonstrate the suitability of using anaerobic digestion in simple unmixed anaerobic digesters for the treatment of a simulant high-strength undiluted human excreta and to quantify the effects of high ammonia concentration on the biogas yield. Ultimately, these studies would support our field research on using anaerobic digesters for the treatment of high-strength undiluted human excreta in developing countries.

Material and methods

Simulant human excreta

The use of real human wastes in laboratory studies can pose health and safety concerns and thus a suitable simulant was developed and used in this study. While using a simulant may not fully represent actual waste, it avoids logistical issues and provides a consistent, well-characterized feedstock.

A modification of the recipes developed by Wignarajah et al. (2006) and Putnam (1971) was developed to prepare the simulated feces and simulated urine, respectively. The major components of feces are fats (5–25$\%_{dw}$), carbohydrates (10–30$\%_{dw}$), nitrogenous materials (2–3$\%_{dw}$), bacterial debris (10–30$\%_{dw}$) and inorganic matter (10–20$\%_{dw}$) (Barman et al., 2009). Urine is mainly composed of inorganic salts (38$\%_{dw}$), urea (36$\%_{dw}$), organic compounds (13$\%_{dw}$) and organic ammonium salts (13$\%_{dw}$) (Putnam, 1971).

Table 1 shows the composition of simulant feces and urine used in this study. Feces simulant composition in % dry weight (dw) was as follows: baker's yeast (30$\%_{dw}$) was used as bacterial debris, microcrystalline cellulose (10$\%_{dw}$) and psyllium (17.5$\%_{dw}$) were used as a carbohydrate/fiber simulant, oleic acid (20$\%_{dw}$) was used for fats and 17.5$\%_{dw}$ of miso was used to adjust nitrogen content as well as other chemical properties. The miso paste composition is given as 38% proteins, 21% fats, 20% fiber and 4% minerals. All chemicals were supplied by VWR (Radnor, Pennsylvania) except miso and psyllium that were purchased at a local grocery store (365 psyllium husk from Whole Foods, and miso was either Miso Master Organic from Whole Foods, or Shirakiku Miso, from Amazon.com). The simulant formulation was adjusted for trace metal contents after day 200 (see Results section for details) by adding a trace element solution to the simulant feces so that the composition was as follows: $FeCl_2 \cdot 4H_2O$, 28.6 $mg\ kg^{-1}_{TS}$; H_3BO_3, 1.14 $mg\ kg^{-1}_{TS}$; $MnCl_2 \cdot 4H_2O$, 1.91 $mg\ kg^{-1}_{TS}$; $CoCl_2 \cdot 6H_2O$, 2.29 $mg\ kg^{-1}_{TS}$; $ZnCl_2$, 1.34 $mg\ kg^{-1}_{TS}$; $NiCl_2 \cdot 6H_2O$, 0.48 $mg\ kg^{-1}_{TS}$; $CuCl_2 \cdot 2H_2O$, 0.29 $mg\ kg^{-1}_{TS}$; $NaMoO_4 \cdot 2H_2O$, 0.48 $mg\ kg^{-1}_{TS}$. The adequacy of the simulant formulation and how it matches real fecal waste is discussed in the Results section.

Table 1

Chemical composition of simulated feces and simulated urine. Stages 3 and 4 refer to different phases during the experiments (see text for details).

Simulant feces		Simulant urine		
Compound	Amount ($g\ kg^{-1}$)	Compound	Amount ($g\ L^{-1}$)	
			Stage 3	Stage 4
Water	800	Urea	9.3	14.2
Baker's yeast (dry)	60	Creatinine	2.0	3.0
Microcrystalline cellulose	20	Ammonium citrate	1.0	2.0
Psyllium	35	NaCl	8.0	8.0
Miso paste	35	KCl	1.65	1.65
Oleic acid	40	$KHSO_4$	0.5	0.5
NaCl	4	$MgSO_4$	0.2	0.2
KCl	4	KH_2PO_4	1.75	1.75
$CaCl_2$	2	$KHCO_3$	0.5	0.5