EFFECTIVE SEWAGE SANITATION WITH LOW CO_2 FOOTPRINT[1]

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ABSTRACT

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. The overall objective of this work is to develop a self-contained and energy neutral sanitation technology that relies on anaerobic digestion of human wastes to generate biogas, and use the biogas to heat-sterilize the treated effluent. An effective heat exchanger increases the efficacy of the heat sterilization. A prototype system consisting of a custom-built floating dome digester, heater and heat exchanger was built. Daily biogas production in the digester was 0.33 m^3_{biogas}/kg_{COD} when feeding feces and urine mimics. The heat-sterilization system had a thermal efficiency ranging from 50 to 70% depending on the working temperature, while the heat exchanger allowed an energy recovery of 800 kJ/day. A sterilization test was carried out using E. coli as an indicator and greater than 7 log-reduction was achieved. This new and simple system shows promise as replacement for pit latrines.

KEYWORDS: Anaerobic digestion, Pathogen control, Pit latrine replacement, Sanitation

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 & Elimelech, 2007). In 2010, an estimated 2.5 billion people were still without improved sanitation, and 1.1 billion people still practice open defecation (World Health Organization, 2012). Sanitation coverage by region shows marked differences. While in developed countries the coverage rate is >95%, many countries are off the track in meeting the Millennium Development Goals sanitation target (i.e., coverage ≥75 %). Southern Asia and Sub-Saharan Africa represent the two regions with a lower sanitation coverage (41 % and 30 % respectively) (World Health Organization, 2012). The use of unsafe sanitation can have serious consequences. 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 1.5 million child deaths (BMGF, 2011).

In light of this, the overall objective of this project is to develop a novel self-contained and energy neutral sanitation technology that relies on anaerobic digestion of the wastes to generate biogas and utilize the biogas thus produced in an effective heat-recovery and heat-sterilization system to eliminate pathogens from the effluent. The basic principle is shown in Figure 1. The expected advantages of this novel technology are:

- Simple low-cost process/equipment, suited for deployment in developing countries
- Effective sanitation of wastes in one single stage without sludge formation
- Self-contained, energy neutral system
- Eliminates methane emissions, a potent greenhouse gas while providing sanitation
- No water is required during daily operation
- Depending on organic loading, system could provide extra biogas for cooking

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- Suitable as a replacement for pit latrine

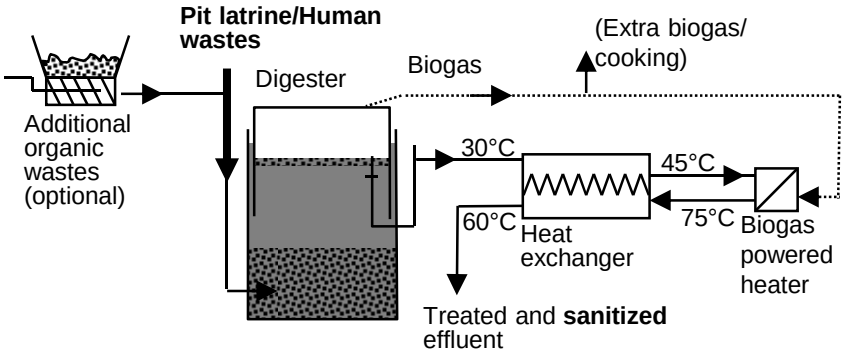

Figure 1. Flowsheet and concept of the novel sanitation technology (not to scale).

This study is divided into two different parts, one is focused on the design and the performance of an anaerobic digester, and the other is focused on the design and the proof of concept of the heat recovery/sterilization system to treat the digester effluent.

RESULTS: ANAEROBIC DIGESTION

The main goal of this effort is to prove the suitability of a mixture of feces and urine to serve as a substrate for efficient anaerobic digestion. The concern is mainly to achieve usual biogas yields and obtain suitable rates of biogas production. The daily amount feces excreted per person ranges between 70 and 520 g_{wet} p^{-1} d^{-1} (Torondel, 2010), and in the absence of local information an amount of 350-400 g_{wet} p^{-1} d^{-1} is proposed as a reasonable average (Wignarajah et al., 2006; Franceys et al., 1992). The volume of urine produced daily per person 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). Thus, an average amount of 400 g_{wet} feces p^{-1} d^{-1} and 1 L urine p^{-1} d^{1} was used in this work. Table 1 shows the chemical properties of the simulant feces and urine and the comparison with actual values for human excreta. The nitrogen content of the simulant excreta is equivalent to 7.25 g N p^{-1} d^{-1} which is in accordance with bibliographic data. Values ranging from 5.2 to 8.2 g N p^{-1} d^{-1} are reported in countries like Uganda, Haiti, India or South Africa (Richert et al., 2010).

A semi-continuous floating dome anaerobic digester with a working volume of 17 liters (lab-scale) was constructed and used in the experiments reported herein. In order to simulate the actual performance of a household full-scale digester treating undiluted human excreta, the reactor operation condition were as follows:

- Hydraulic retention time: 40 days
- Temperature: 30 ± 1°C
- No mixing was provided
- Organic loading rate 1.8 $kg_{COD}/(m^3_{reactor}$ day), where COD is the chemical oxygen demand
- 5.3 g N/L influent
- Sludge removal: none

The feces and urine mixture was fed manually once a day. During the start-up, the organic loading rate was increased from 0.5 to 1.8 g COD L^{-1} d^{-1}, and the total nitrogen was incrementally increased starting from a value of 0.6 g/L. Figure 2 shows the biogas production (in Normal L of gas per g COD, or NL gas/g COD) during the entire experiments as well as the organic loading rate (OLR) and the nitrogen inlet concentration. After the start-up phase (conducted at OLR=1.8 and N_{in}=3.7 g/L) during which microorganisms growth and acclimation occurred, an average of 13.55 L biogas/d were produced with a biogas yield of 0.39 NL biogas/ g COD (see days 75-100). After 100 days of continuous operation, the nitrogen concentration was increased to 5.3 g N/L. This triggered a decrease in the biogas production, and after a slightly recovery (from day 130 onwards) the biogas production stabilized at an average of 11.6 L biogas/d and a biogas yield of 0.33 NL biogas/g COD. The methane content of the biogas remained constant during the whole experiment with an average value of 65 ± 2 %. For indication, the system is roughly 1:30 scale, and thus a full-scale digester for an extended family of 10 would have roughly a sludge volume of 0.6

m^3, or a total volume of about 1.5 m^3 when considering design safety factors and gas headspace. It would produce about 350-400 liters of biogas per day.

Table 1. Simulant feces and urine physicochemical properties.

Property	Simulant feces	Real feces	Property	Simulant urine	Real urine
Moisture (%)	80	65-85 (Wignarajah et al. 2006)	moisture (%)	97.6	95-98 (Putnam, 1971)
TS (%)	20	15-35 (Wignarajah et al. 2006)	TS (%)	2.4	2.5-3.7 (Putnam, 1971)
VS (%)	80	-	VS (%)	60	-
COD (g COD/g TS)	1.23	1.24 (Jönson et al., 2005)	COD (g COD/L)	4.8	3.8-8.2 (Jönson et al., 2005)
COD_s (g COD/g TS)*	0.85	-	COD_s (g COD/L)*	0	-
COD_{dis} (g COD/g TS)*	0.38	-	COD_{dis} (g COD/L)*	4.8	-
N_{tot} (% dry matter)	2.55	2-3 (Barman et al., 2009)	N-tot (mg/L)	5200	5000-8000 (Putnam, 1971)
$N\text{-}NH_3$ (% N_{tot})	3.02	<7 (Jönson et al., 2005)	$N\text{-}NH_3$ (mg/L)	197	<100 (Jönson et al., 2005)
			P_{total} (mg/L)	400	400-1000 (Putnam, 1971)
pH (1:5 w:v)	5.30	4.6-8.4	pH	6.05	6-8.2 (Putnam, 1971)
Coduct. (1:5 w:v, mS/cm)	5.7	-	Conduct. (mS/cm)	23	16-22 (Putnam, 1971)

*COD_s = COD of solids fraction. *COD_{dis} = COD dissolved.

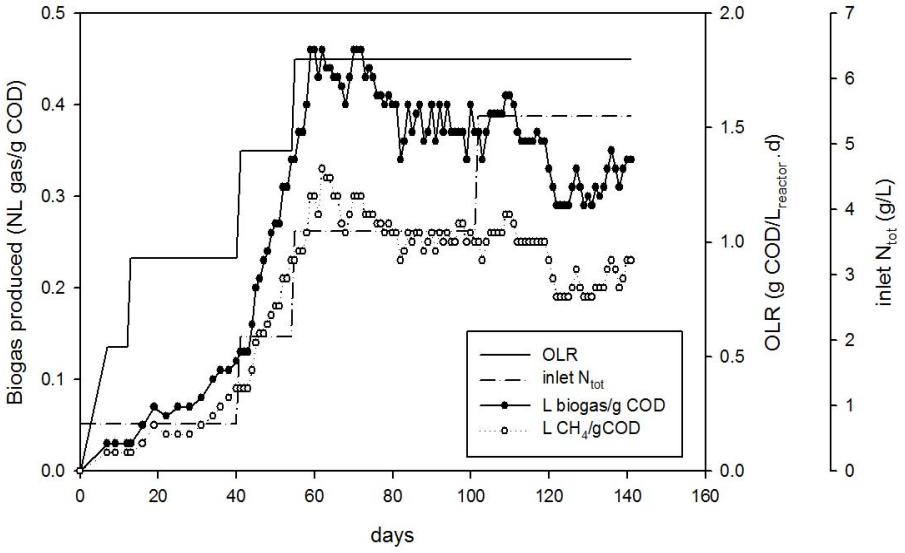

Figure 2. Daily gas production and general operation of the digester during the experiment.

Figure 3 shows the total COD removal efficiency during the same timeframe. The results indicate an average total COD (COD_t) removal in the range of 80 to 85%. Detailed analysis of COD (not shown) reveals good removal (90-95 %) of suspended COD, while dissolved COD was less removed with values ranging from 50 to 65%. This was due to the high accumulation of volatile fatty acids (VFAs), mainly acetic, with concentrations up to 5 g/L.

It is relevant to conduct a COD balance over the anaerobic digester. All COD that enters the digester ends up in either in the end-product CH_4, leaves the digester in the liquid effluent, or is incorporated in new bacterial mass. For that reason a COD balance is generally taken as a control tool for anaerobic digesters. Since both methane and COD in the liquid effluent were monitored, the COD balance can be used to estimate the amount of biomass formed. The balance was made for a period of 40 days (from day 71 to 110). The results shows that 74.6% of the influent COD_{in} was recovered as CH_4, 15% of the COD_{in} was found

at the effluent liquid and thus the balance (10.3%) of the COD_{in} was incorporated as new bacterial mass. With the OLR of 1.8 $kg_{COD}/(m^3_{reactor}$ day) and an average COD of cells of 1.4 kg_{COD}/kg_{dw},, this represents roughly a dry biomass production of 0.13 $kg_{dw}/(m^3_{reactor}$ day). More research, in particular with actual feces and urine, is needed to refine this number and understand the true rate of biomass accumulation under actual field conditions.

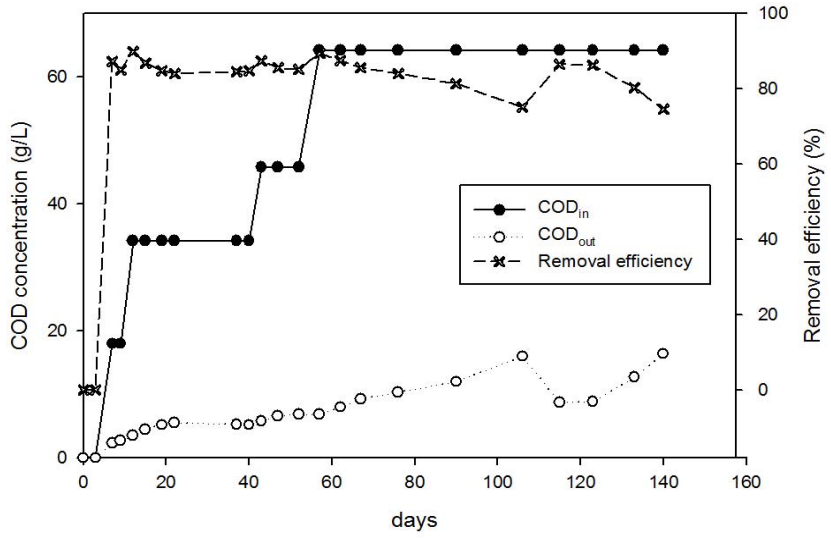

Figure 3. COD_t removal efficiency during the experiment.

Overall, the data presented in Figures 2 and 3 and the COD balance demonstrate that efficient anaerobic digestion can be obtained using undiluted human excreta as a feedstock. A well-adapted bacterial inoculum can effectively convert wastes to biogas even in the presence of high ammonia and VFA concentrations.

RESULTS: HEAT STERILIZATION SYSTEM

A low-cost system that uses the biogas produced during the anaerobic process to heat-sterilize the treated sewage effluent with an efficient heat recovery was designed and tested. Figure 4 shows the heat-sterilization system which comprises a heater (6.8 L) and a countercurrent heat exchanger (2.8 L) for a heat recovery. It is designed to treat 14 L/d of waste (full-scale for 10 people daily generation) and works with discontinuous charges (600 mL/charge) in order to simulate the real field conditions of a pit latrine. The system is simple and has no moving parts.

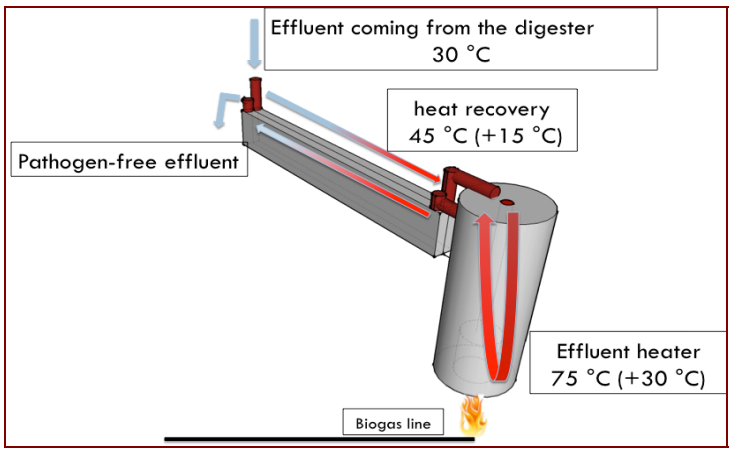

Figure 4. Schematic of the heat-sterilization system (not to scale).

Both the heat exchanger and effluent heater are constructed using common and cheap materials (paint/food can, steel sheet, simple tubing) and thus the entire system can be constructed locally with commonly available materials. It is well known that short exposure to temperatures ranging from 55-75 °C provides several log reductions of bacteria, virus, and helminth ova (Popat et al. 2010). The thermal efficiency (not yet optimized) of the effluent heater exceeds 50% as shown in Figure 5.

The countercurrent heat exchanger is capable to recover energy from the stream leaving the heater and heat the digester effluent by 14 ± 1 °C when the effluent heater is working at 75 °C which corresponds to an energy savings close to 800 kJ/d, reducing the biogas consumption by 15-20 %.

A biogas flow rate of 230 – 280 L_{biogas}/d is enough to maintain the heat-sterilization system between 65 and 75 °C with a normal loading. This is an estimated 60-70 % of the total biogas produced in the anaerobic reactor, thus leaving surplus gas (~150 L/d) for other uses.

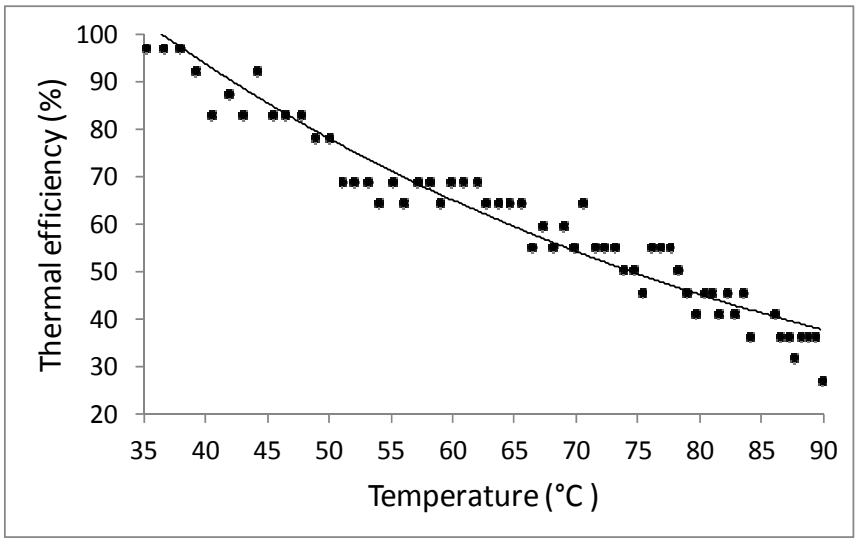

Figure 5. Thermal efficiency of the effluent heater

To demonstrate the efficiency of the heat-sterilization system to inactivate pathogens, two tests were conducted using *Escherichia coli* as an indicator organism. Samples from four collections points and a cumulative sample were collected: heat exchanger inlet, before effluent heater (BEH), after effluent heater (AEF), system outlet and cumulative system outlet. The cumulative effluent outlet was simply the collection of all liquid leaving the system. Experiments were conducted at two different heater temperatures (65 and 75 °C). After 24 h of continuous operation (14 L/d, 600 mL per charge once per hour), samples were taken and viable cell counts were performed.

The results (Figure 6) show an initial concentration greater than 10^7 CFU/mL depending on the experiment, and complete elimination of *E. coli* at both temperatures in the effluent of the heater. A complete inactivation of *E. coli* is observed after the effluent heater and no viable cells were found in the cumulating sample. These results represent at least 7 log reductions. Detailed examination of Figure 6 shows that a higher *E. coli* inactivation is achieved in the heating segment of the heat exchanger (about 2 log reductions) at 75 °C compared to 65 °C. This is because of the higher temperatures reached in the former case. During the 65 °C experiment, viable cell reduction in the heat exchanger was low.

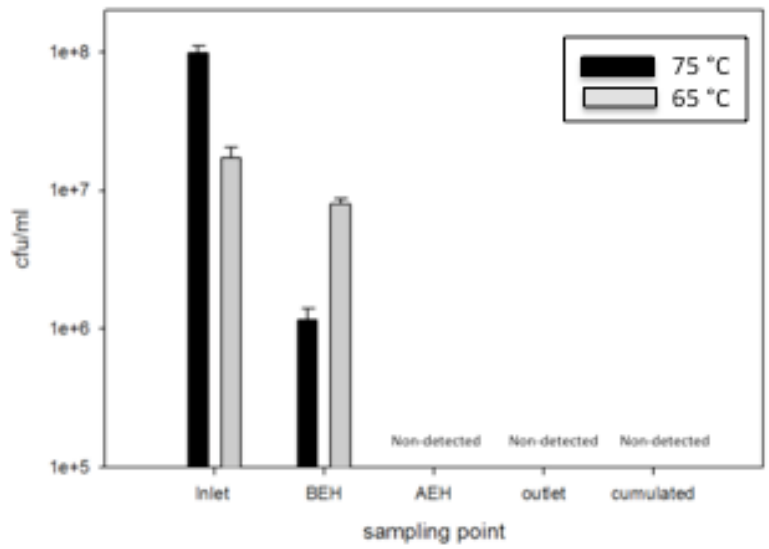

Figure 6. *E. coli* viable cell counts during indicator organism disinfection experiment: BEH: before effluent heater; AEH: After effluent heater.

CONCLUSIONS

The novel sanitation system appears to be very promising. The system meets the objectives to effectively treat human waste with high removal efficiencies of COD and effective pathogens control in the heat-sterilization unit. These objectives are met while requiring no energy or water inputs, and perhaps even providing a resource in excess biogas.

Research is underway to optimize biogas production, and improve the design and thermal efficiency of the heat sterilization system. Further, pathogen disinfection experiments with virus and helminth ova are being considerd. Demonstration of the efficacy of the system as a replacement for pit latrines in the field is warranted. Duke has ongoing civic engagement and development projects in a number of countries including Uganda, Peru, Columbia, Honduras, etc. which can provide the necessary framework for such field demonstrations.

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