Methane Production for Sanitation Improvement in Haiti

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Abstract

There is a great need for decentralized anaerobic digestion (AD) that utilizes wastewater for energy generation. The biochemical methane potential (BMP) of Haitian latrine waste was determined and compared other waste streams, such as grey water, septage, and dairy manure. Average methane (CH_4) production for the latrine waste (13.6 ml ml^{-1} substrate) was 23 times greater than septage (0.58 ml ml^{-1} substrate), and 151 times greater than grey water (0.09 ml ml^{-1} substrate), illustrating the larger potential when waste is source separated (DESAR) for more appropriate treatment of each waste stream. Using the BMP results, methane production based on various AD configurations was calculated, and compared with the full-scale field AD design. Methane potential from the BMP testing was calculated as 0.006 to $0.017 \text{ m}^3 \text{ person}^{-1} \text{ day}^{-1}$ using the lowest and highest latrine BMP results, which was similar to the values from the full-scale system ($0.011 \text{ m}^3 \text{ person}^{-1} \text{ day}^{-1}$), illustrating the ability of BMPs to be used to predict biogas production from sanitation digesters in a smaller-scale setting.

Keywords:

Anaerobic digestion; biogas; biochemical methane potential (BMP); pit latrine; wastewater; grey water

1.0 Introduction

1.1 Sanitation Needs in Haiti

It is estimated that 37% of the world population (2.5 billion people) do not have access to improved sanitation, with 1.1 billion people practicing open defecation due to limited access to the resources needed to properly collect and dispose of waste [1]. This results in poor water quality accounting for up to 1.7 million deaths per year (3.1% of world deaths/year) [2]. The country of Haiti serves as an example where sanitation and energy needs are some of the most pressing, with no centralized sewage treatment and less than 27% of the population having access to improved sanitation [1]. The 2010 earthquake and on-going cholera outbreak in Haiti highlighted the dire consequences of inadequate waste treatment, with 734,134 reported cholera cases and 8,896 confirmed deaths due to cholera as of 28 February 2015 [3].

In the U.S., approximately 0.5 kWh of electricity is needed to treat each m³ of wastewater, accounting for 3% of all U.S. electricity use [4]. In Haiti, feasibility studies revealed that construction, operation, and maintenance costs for centralized wastewater treatment would exceed the local capacity to pay [5]. Additionally, the country's electric grid provides irregular coverage to only 10% of the population, with wood and charcoal representing 70% of the energy use within the country. Cooking fuel is estimated to require 25-50% of daily income [6], or \$6-10 per family per week in charcoal expenses for cooking. The continual use of charcoal and firewood for basic energy needs has resulted in soil erosion and deforestation throughout the country, leaving only 1.5% of the land forested [6].

Energy-neutral, land-based treatment methods (e.g. lagoons and stabilization ponds) have proven effective in rural areas; however, they require centralized collection and a large footprint. The effectiveness of pit latrines is greatly dependent on the characteristics of the underlying soils and hydrology. Dry, composting latrines have been implemented in a number of developing countries, including successful implementation by Sustainable Organic Integrated Livelihoods (SOIL) in Haiti. However, payment for this technology relies solely on the economic value of fertilizer, requires a constant carbon source input, and does not exploit the biochemical energy of waste: 4.41 kWh of energy in each kg of sugar or per 1.06 kg of chemical oxygen demand (COD) [7].

1.2 Anaerobic Digestion

An anaerobic digester can harness a significant proportion of the potential energy in wastewater, with a reported 0.17 m³ of methane (CH₄) produced per m³ of domestic wastewater, assuming a dilute combined grey water and black water sewage wastewater influent chemical oxygen demand (COD) concentration of 0.8 g L⁻¹, with 60% conversion of COD to CH₄ [8]. During anaerobic digestion (AD), a consortium of microorganisms break down the organic matter (COD) in the waste, resulting in the production of biogas with 55–75% CH₄, which can be used for cooking, heating, or electricity generation. The AD process results in the stabilization of the treated waste through large reductions in solids, pathogens, and odors, and the creation of a high nutrient soil amendment [9,10].

The USEPA [11] stated that the main barriers to the widespread adoption of AD technology in the U.S. are the cost and sophistication of the operating equipment. In

contrast, low-cost non-mechanized AD designs, such as the plug-flow, Taiwanese-model digester and other similar tubular plug-flow designs, have successfully treated agricultural manure in Latin America and Asia with minimal energy inputs. In tropical climates, where mesophilic (20-45 °C) digestion can be maintained without heating, such AD designs have been shown to produce viable quantities of CH₄ and large reductions in organic waste [12, 13]. To date, there are over 100,000 Taiwanese-model systems in tropical areas of Asia and Latin America, with the vast majority used to treat dairy and swine manure [14]. There are far fewer plug-flow systems utilizing only human waste as the digestion input, with little to no published data, largely due to the lower solids content, conveyance difficulties, and pathogenic concerns with human waste. Based on the success of the agricultural-based AD systems in similar resource-limited settings, their potential as a viable and sustainable sanitation solution for Haiti was quantified.

1.3 DESAR: Decentralized Sanitation and Reuse

An AD system can use the Decentralized Sanitation and Reuse (DESAR) concept to separate black water (originating from toilets: feces, urine and flush water), and grey water (originating from washrooms, showers and kitchens) for more appropriate treatment of these different waste sources. Studies have shown that in domestic wastewater, 51% of chemical oxygen demand (COD), 91% of nitrogen, 78% of phosphorus, and the majority of the pathogens are contained in black water [15]. Separately treating black water results in a decrease in AD reactor size, thereby reducing capital costs and space requirements [15, 16]. Studies have shown that when black water is separated and anaerobically digested, recovery and reuse of the more concentrated

dissolved nutrients in the AD effluent becomes more feasible [15, 17]. While previous studies stated that DESAR is especially applicable to developing countries [18, 19], there is a lack of literature regarding use of DESAR in developing countries, like Haiti, where treatment of black water in septic or latrine systems and direct discharge of grey water is more common.

1.4 Research Objectives

The majority of research on AD of wastewater has focused on activated sludge digestion at wastewater treatment plants or manure-based digesters but little research has been conducted on treating human wastewater through AD at the small-scale. This research sought to understand the biochemical methane potential (BMP) of the latrine waste, compare them to other waste streams, such as grey water and dairy manure, and verify CH₄ production and treatment potential using a full-scale, low-cost sanitary digester in Haiti. Specifically, the objectives were to: (1) determine the BMP of source-separated wastewater sources, including grey water, septage pit, and latrine waste, from a hospital in rural Haiti; (2) estimate CH₄ potentials with various AD design configurations through modeling calculations; and (3) compare CH₄ production from the full-scale DESAR AD system to the calculated BMP values.

2.0 Materials and Methods

2.1 Site Description

The Partners in Health (PIH) medical complex in Cange is situated sixty miles northeast of Port-au-Prince, Haiti (18°55'0N; 71°58'60W) and provides healthcare to approximately 2,000 people per day from the local rural population and includes an outpatient clinic, serving 100-400 patients a day, and a 1,000-student K-12 school. The PIH complex has two types of toilets: flush toilets that convey the black water from the toilet into septage pits and dry latrine privies situated above larger septage pits. Grey water from the hospital and clinics operating rooms is also directed to septage pits. Grey water from other sinks, showers, and laundry areas is not stored in septage pits, but instead flows over a trickling rock filter before discharge into a ravine. Overall, the PIH complex has 17 septage pits that receive a combination of black water from 86 flush toilets, latrine waste from five latrine structures with multiple privies, and grey water from the hospital operating rooms and clinics.

2.2 Sample Collection for Biochemical Methane Potential (BMP) Analyses

To characterize the waste and perform biochemical methane potential (BMP) testing, grab samples were taken during seven collection periods from March 2010 to June 2012 from three wastewater sources: latrines, septage pits and grey water. No separate black water samples were collected, as the black water pipes are inaccessible, entering the septage pits underneath the latrine feces. The wastewater collected from *Latrine 1*, the School latrine pit, received latrine waste from 1,000 children and black water from three toilets used by 15 teachers and 5 residents. *Latrine 2*, the Outpatient

Clinic latrine, received latrine waste from 350 patients and black water from 7 toilets used by 5 clinic staff members and 3-5 foreign visitors. The *Hospital Septage Pit* received black water from 12 Hospital toilets and grey water from sinks and showers within the hospital ward and operating rooms. *Grey Water 1* was a mixture of all the grey water sources (*Grey Water 2-4*) in the PIH complex. *Grey Water 2* originated from sinks and showers in the Outpatient Clinic. *Grey Water 3* originated from the Hospital Kitchen and *Grey Water 4* from the Hospital sinks and showers. In addition, freshly excreted dairy manure from local dairy cows in Cange was analyzed to determine how the latrine waste compared with the more traditional input (dairy manure) in Taiwanese-model digestion systems.

All samples were transported on ice from Haiti to College Park, MD within two days of collection and stored at 4°C. Samples were analyzed for pH, COD, total solids (TS), and volatile solids (VS), according to Standard Methods [20]. Significant differences in these environmental characteristics and CH₄ production (cumulative CH₄ and percent CH₄) were statistically analyzed using analysis of variance (ANOVA) and Tukey–Kramer multiple comparisons. P-values < 0.05 were considered significant. All values are reported as averages ± standard error (SE).

2.3 Biochemical Methane Potential (BMP) Testing

The BMP experiments were conducted using samples from four sample collection periods (BMP1: June 2010, BMP2: October 2010, BMP3: January 2011, and BMP4: June 2012). The BMP assay was developed to determine the CH₄ yield of organic material during AD by a mixed microbial community in a defined medium [21, 22]. For

the BMP experiments, the substrate was incubated under anaerobic conditions for 30-70 days (until the biogas production largely ceased) in triplicate 250 mL serum bottles (200 mL liquid volume and 50 mL headspace) with inoculum and nutrient media at 35°C [22]. The inoculum provided an enriched source of bacteria, including methanogens acclimated to an anaerobic environment, thereby reducing the lag time in CH₄ production. Mineral media was prepared according to Moody et al. [23], which was adapted from ASTM [22]. The media contained 6 g/L sodium bicarbonate as a pH buffer and 18 micro and macronutrients to assure that nitrogen, phosphorus, potassium and micronutrients were not limiting CH₄ production. In BMP4, bottles were prepared with and without media to determine the effect of media on CH₄ production with latrine waste.

Before incubation, the BMP bottles were flushed with 70:30 N₂:CO₂ to ensure anaerobic conditions. Biogas volume was measured volumetrically using a glass, gas-tight syringe equilibrated to atmospheric pressure. Biogas samples were analyzed for CH₄ composition using a HP 5890 Series II Plus gas chromatography (GC) with flame ionization detector (FID), with an injection temperature of 200°C, a detector temperature of 250°C, and helium as the carrier gas at a flow rate of 300 ml/min. Biogas production and CH₄ content were measured daily during the first week of the experiment, approximately every other day the following week, and then bi-weekly for the remainder of the experiment, with measurement frequency based on the quantity of biogas produced.

To account for biogas production from residual degradable matter in the digester inoculum, triplicate control bottles containing only media and inoculum were incubated and sampled simultaneously to account for CH₄ production not attributed to the substrate.

Inoculum for BMPs 1-3 was obtained from a dairy manure AD at USDA's Beltsville Agricultural Research Center (BARC), and inoculum for BMP4 was obtained from a sanitary wastewater AD at the Alexandria, VA wastewater treatment plant. The average value from the inoculum control bottles was subtracted from all reported CH₄ data to account for CH₄ production not attributed to the substrate.

INSERT TABLE 1

The inoculum to substrate ratio (ISR) is reported using normalizations by volume and VS (Table 1). The experimental design varied for each BMP due to differences in inoculum and waste source VS concentrations. BMP 4 was loaded using a 1:1 ISR (by VS) using inoculum from a sanitary wastewater AD. In BMP1-BMP3, various modified VS-based ISRs were used due to the lower VS of the dairy manure AD at BARC. If a 1:1 ISR was used, < 3 ml of inoculum would have been added to each 250 ml grey water BMP bottle and < 3 ml of latrine substrate would have been added to each latrine bottle due to the large differences in VS concentrations of these substrates compared to the control, and therefore, adjustments were made to the ISR to increase the amount of inoculum in the grey water BMP bottles and increase the quantity of latrine substrate in the latrine BMP bottles (Table 1).

2.4 Calculations of Methane Potential for the Full-Scale AD Design

The PIH AD system design process began with clicker counts of potential latrine users at the PIH complex over a 3-week period from sunrise to sundown to determine: 1)

the number of users entering each existing latrine, and 2) the number of potential users forgoing the latrine for open defecation in the immediate area. The results showed a daily average of 209 potential users (ranging from 120 to 351) at the outpatient latrine site, but only 38% actually used the latrine facilities with the remaining practicing open defecation. To account for daily variation, wastewater flows were estimated for 50-500 daily uses, with an assumed 50% reduction on weekends based on reductions in staffing and patient population. It was assumed that the same person could be a user multiple times, and therefore the number of users per day was expected to be five times higher than the patient and staff population.

Waste composition and production for PIH were estimated using a per capita daily waste production of 1.2 L of urine and 520 g (wet weight) of fecal matter based on Polprasert [24], which accounted for dietary and cultural factors affecting human waste in the developing world. The density and moisture content of fecal matter was estimated to be 1.4 g/cm³ and 83%, respectively [25]. The daily waste production rate per capita was divided into five latrine uses per day, consisting of three urinations and two defecations, in order to determine wastewater content on a 'per use' basis.

Daily wastewater production was estimated for several waste conveyance strategies: (1) digestion of latrine waste in-vessel with no conveyance water; (2) bucket flush (0.5 L of conveyance water); (3) low flush toilets (4 L of conveyance water); and (4) low flush toilets (4 L) with urinal waste diverted from the AD system. The AD system size was calculated for each wastewater scenario using a 47-day retention time, and potential CH₄ production was calculated using values derived from the BMP testing.

2.5 PIH Anaerobic Digestion (AD) Full-Scale Design and Testing

Due to the preferences of the managers on-site the AD system for the PIH outpatient clinic was designed with low-flush toilets (4 L of conveyance water), with the black water conveyed to a three-cell, 36 m³ AD system with post-treatment subsurface wetlands (28.4 m³). Each digester has a liquid phase of 12 m³, with 10 m³ of combined gas space within the three-cell AD system. The wetland has gravel substrate with a void volume of 0.5, creating an effective treatment volume of 14.2 m³. The urinal waste and sink grey water were conveyed in accordance with the DESAR concept, proceeding directly to the post-treatment wetlands (wastewater conveyance strategy #4 above), in order to reduce flush water and nitrogen concentration in the digestion system and provide more appropriate treatment of the black water and grey water waste streams (Figure 1).

The AD system began receiving black water in October 2013, with dairy manure used as the inoculum source to increase biogas production during the start-up phase. Samples were collected from the full-scale system over seven sampling events during a seven month period beginning in April 2014, with samples analyzed both in Haiti at the Université Quisqueya laboratory and in the USA at the University of Maryland Water Quality Laboratory, using standard methods for total coliforms, fecal coliforms, pH, alkalinity, COD, TS, and VS [21]. Biogas production was measured with a low-flow gas meter (EKM ¾" Pulse Output Gas Meter, Santa Cruz, CA, USA) and CH₄ and H₂S were measured on-site with a Biogas 5000 meter (LANDTEC, Colton, CA, USA).

INSERT FIGURE 1

3.0 Results and Discussion

3.1 Biochemical Methane Potential (BMP) Experiments

The latrine waste and dairy manure used in the BMPs were not significantly different from each other in TS, VS and COD concentrations, highlighting the high organic matter content and biogas potential of both latrine waste and dairy manure, with dairy manure being the more traditional AD input in the developing world. The VS and COD concentrations of the latrine waste (133 and 456 g L⁻¹, respectively) and dairy manure (110 and 558 g L⁻¹, respectively) were an order of magnitude greater than the septage (12.3 and 12.8 g L⁻¹, respectively) and two orders greater than the grey water (6.8 and 3.3 g L⁻¹, respectively) (Table 2) (p-value < 0.001). The COD, TS and VS concentrations of the septage were not significantly different from the grey water (p-value > 0.9), likely due to the addition of hospital grey water to the septage pit, resulting in dilution of the septage waste. The average pH of the latrine, grey water and septage were 7.61, 7.51, and 7.19, which is within the ideal range (7-8) for CH₄ production.

INSERT TABLE 2

The organic matter concentration correlated with cumulative CH₄ production from the BMP experiments when normalized on a volumetric basis (Tables 1, 2; Figure 2A). The average cumulative CH₄ production for the latrine waste for all four BMPs was 13.6 ml ml⁻¹ substrate, which was 23 times greater than the septage pit (0.58 ml ml⁻¹ substrate), and 151 times greater than the grey water (0.09 ml ml⁻¹ substrate). These results were expected when normalizing CH₄ production by waste volume, but higher

than the differences in the VS concentration would imply, with the latrine sludge having only 11 and 20 times more VS than the septage pit and grey water, respectively. The average CH₄ production values for the grey water (0.09 ml ml⁻¹ substrate) were similar to average CH₄ production from traditional sewage input from industrialized countries (0.13 ml ml⁻¹ substrate), which is more dilute (0.8 g L⁻¹ COD) to the wastewater sources in this study due to decreased water use in a resource limited setting, like Haiti [8]. The latrine CH₄ production values were almost exactly two orders of magnitude greater on a volumetric basis (13.6 ml ml⁻¹ substrate) compared to traditional sewage input due to the concentration of organic matter in the latrine waste.

INSERT FIGURE 2

The BMP results were also normalized to the quantity of VS added to each bottle (Table 1; Figure 2B). This normalization describes the efficiency in converting the carbonaceous material present in the digestion vessel into CH₄. When normalized by VS, the average CH₄ cumulative production from the latrine waste (99.0 ml g⁻¹ VS) was almost three times higher than the septage (35.6 ml g⁻¹ VS) and four times higher than the grey water (24.3 ml g⁻¹ VS). Cumulative CH₄ results for each individual BMP, with Tukey-Kramer statistical differences after 30, 47, and 70 days of digestion, are shown in Table 3.

INSERT TABLE 3

While the grey water sources in BMPs produced approximately one-third of the CH₄ production of the latrine wastes on a per gram VS basis, due to the dilute nature of the grey water, an AD would need 151 times more substrate, and thus 151x AD volume, to achieve similar CH₄ production levels to a latrine-based AD. Based on the low VS concentration in the grey water and the low CH₄ production, with no CH₄ production from the grey water in BMP3, it was determined that the grey water would be more effectively treated directly in post-treatment wetlands. Li et al. [26] stated in their review of grey treatment that constructed wetlands are considered one of the most environmentally friendly and cost-effective technologies for grey water treatment. The lower CH₄ production efficiencies of the grey water and septage pit in BMP3 could be due to bacteriocidal agents, such as iodine, in the grey water from the hospital operating room. An anaerobic toxicity assay (ATA) was conducted on the septage, and direct toxicity was not shown (data not shown). If grey water were directed to the digester, further testing would be needed to determine if the concentration of contaminants, such as antibiotics and iodine, in the hospital grey water could be inhibitory to digestion over time.

The asymptotes in the cumulative CH₄ production (Figure 2) showed that the waste sources should be digested for at least 30 days to capture the majority of the CH₄ production potential. The lowest and highest CH₄ producing latrine waste sources (latrine waste in BMP1 and BMP2, respectively) produced an average of 0.25 and 0.57 ml ml⁻¹ substrate day⁻¹, respectively, during the first 30 days of digestion. In BMP4, 90% of the CH₄ production from the latrine waste and 80% from the septage pit CH₄ was produced by Day 30, resulting in average CH₄ production rates during the first 30 days of digestion

of 0.55 and 0.015 ml ml⁻¹ substrate day⁻¹, respectively. In BMP2 and BMP3, the latrine waste produced 81% and 93% of total CH₄ production by Day 30, and 94% and 97% by Day 47, respectively.

While there were two types of inoculum used in the BMPs experiments, dairy manure digestate for BMPs 1-3 and municipal wastewater digestate for BMP4, there was not a significant inoculum source effect in the 30-day cumulative CH₄ production (p-value = 1.0). The largest CH₄ potential from the latrine waste was observed in BMP2 and the lowest in BMP1, both of which had dairy manure digestate as the inoculum source (Table 3). The ISR also did not show a significant effect on CH₄ production, with no significant differences between cumulative CH₄ production from the latrine waste with the highest ISR value (1:1 in BMP4: 18.5 ml ml⁻¹ substrate and 136 ml g⁻¹ VS), and the lowest ISR value (1:4 in BMP2: 21.0 ml ml⁻¹ substrate and 137 ml g⁻¹ VS), which had the highest CH₄ production levels (on a VS basis) of all latrine waste sources. The ability of latrine-based digesters to produce high quantities of CH₄ with dairy digestate at lower, non-limiting ISRs is promising for a resource-limited setting like Haiti. Dairy manure was not statistically different in TS, COD and VS concentrations from the latrine waste, nor was there a statistical difference in CH₄ production between dairy manure and the latrine waste results for BMPs 2 and 4 (Table 3; p-value = 0.22). Dairy manure has been used successfully digested in the small-scale AD systems throughout the world, and these results show that latrine waste could also be used as a viable substrate in small-scale AD.

Standard BMP nutrient media was used in each BMP, except in BMP4 where the latrine and septage substrates were digested with and without media to determine if the additional nutrients and alkalinity in the media were needed for digestion. There was a

3.9% decrease in cumulative CH₄ when the latrine waste was digested without media, however this decrease was not statistically significant, (17.8 and 18.5 ml ml⁻¹ substrate respectively; p-value = 0.58). There was a significant effect when the septage pit was digested without media (0.4 and 0.6 ml ml⁻¹ substrate, respectively; p-value = 0.049), likely due to possible toxins or the lack of micronutrients in the dilute wastewater resulting in a decrease in methanogenic activity. These findings are consistent with the hypothesis that digestion of hospital septage, which was mixed with hospital grey water, may present significant challenges that were not inherently found in digesting only latrine waste.

3.2 Calculated Methane Potentials for the Full-Scale AD Design

The quantity of fecal matter and total volume entering the AD for the four wastewater conveyance strategies were calculated based on the number of users and a 47-day retention time (Table 4). A 47-day retention time was chosen based on the BMP results, which showed an average increase in cumulative CH₄ production from latrine waste of 10% when extending the 30 to 47 days, but only a 4% increase in CH₄ production with an additional 19 days of digestion (Day 47 to Day 66). The calculated CH₄ production values for a full-scale AD system were determined based on the highest (BMP2: 21.3 ml ml⁻¹ substrate) and lowest (BMP1: 7.5 ml ml⁻¹ substrate) latrine CH₄ production results (Table 4). The size of the digester needed for the four waste conveyance strategies varied from 1.2 m³ (50 people with no conveyance water) to 92.4 m³ (500 people with low flush toilets). The predicted CH₄ potential increased with number of users, ranging from 0.06 m³ day⁻¹ with 50 users and the lowest CH₄ production

value to $1.7 \text{ m}^3 \text{ day}^{-1}$ with 500 users and the highest CH_4 production value. Utilizing the average percent CH_4 of the latrine waste BMPs (62.9%), the calculated quantity of biogas produced ranged from $0.1 - 2.7 \text{ m}^3 \text{ day}^{-1}$ with 50 and 500 users day^{-1} , respectively. Assuming 5 uses $\text{person}^{-1}\text{day}^{-1}$ and using the highest latrine BMP CH_4 production results, the average CH_4 production was calculated to be $0.017 \text{ m}^3 \text{ person}^{-1}\text{day}^{-1}$ ($0.003 \text{ m}^3 \text{ user}^{-1}\text{day}^{-1}$). This estimate is comparable to a previous study, which found low-tech digestion systems with black water mixed with kitchen waste to have CH_4 production values of $0.02 \text{ m}^3 \text{ person}^{-1}\text{day}^{-1}$ [20].

Based on BMP results and the sanitation preferences at the PIH complex, four low flush toilets (4 L per flush) were piped directly to a 36 m^3 AD system digester, with waste from one urinal and grey water from one communal sink routed directly the post-treatment wetland (Figure 1). With the 4L flush volume, the expected COD value of the digester influent (114 g L^{-1}) was 20% greater than the black water value of Kujawa-Roeleveld et al. [16] at 90 g L^{-1} , which had vacuum toilet black water entering an AD. The calculated raw feces COD value of 550 g L^{-1} was 18% greater than the average latrine COD concentration for the waste used in the BMPs (456 g L^{-1}).

The expected grey water and urinal volume to the wetlands was calculated to range from $0.31 \text{ m}^3 \text{ day}^{-1}$ (50 users) to $3.13 \text{ m}^3 \text{ day}^{-1}$ (500 users) based on 2 L of grey water per user, resulting in a wetland loading rate of 0.024 to $0.24 \text{ kg COD m}^{-3} \text{ day}^{-1}$, which is below typical COD loadings for tropical treatment wetlands ($1.0 - 2.8 \text{ kg COD m}^{-3} \text{ day}^{-1}$) [27], allowing for the additional expected COD input from the treated digester effluent ($0.015 - 0.13 \text{ kg COD m}^{-3} \text{ day}^{-1}$) to also be effectively treated in the wetland system. While grey water has been documented to contain a significant amount of the

COD in domestic wastewater (41%) [18, 28], the grey water at the Cange digestion system comes only from hand washing, and will likely contain less COD than complex grey water, which includes kitchen and laundry grey water sources.

3.3 Treatment Results from Full-Scale Sanitary Digester

The biogas production from the operational PIH digestion system averaged 0.108 m³ day⁻¹, with an average of 65.4% CH₄ in the biogas (618 ppm H₂S), the CH₄ production averaged 0.071 m³ day⁻¹. The average usage of the toilets during this period was only 31 uses day⁻¹, resulting in a CH₄ production value of 0.002 m³ use⁻¹ day⁻¹ (0.011 m³ person⁻¹ day⁻¹ based on 5 uses per person in one day), which was 35% lower than the calculated CH₄ value from the highest performing latrine BMP (0.017 m³ person⁻¹ day⁻¹), but 46% higher than the calculated CH₄ value from the lowest performing BMP (0.006 m³ person⁻¹ day⁻¹). Based on the VS and volumetric loading of the full-scale system, the CH₄ production was 16% higher than the average latrine BMPs (118 ml g⁻¹ VS added), likely due to the more efficient digestion process in a continuous system compared to the batch BMPs, but 96% lower on a volumetric basis (0.50 ml ml⁻¹ substrate) due to the large volume of flush water (4 L) compared to the calculated sanitary waste expected (0.59 L) on a per use basis and lower influent COD value (6.11 g L⁻¹).

The PIH CH₄ production levels should increase as the number of users increase. The number of users averaged 31 users per day for the first 8 months, but is expected to increase to 500 users per day with black water from the school low flush toilets plumbed into the digestion system beginning in March 2015. Increasing user numbers as well as adding even small amounts of kitchen food waste to the digestion system should increase

CH₄ production [32]. Food waste addition will be considered once the full-scale system stabilizes from the increased loading from the additional users. Kujawa-Roeleveld et al. [16] showed that by separating urine and only including black water and kitchen waste in the AD systems, CH₄ production rose 48% to 0.036 m³ person⁻¹day⁻¹ with urine diversion, likely due to less NH₄-N inhibition with urine diversion; a motivating factor for urine diversion in our final digestion system.

The average NH₄-N concentration in the full-scale system was 0.16 g NH₄-N L⁻¹, which was 89% lower than the latrine waste in BMP4 (1.52 ± 0.04 g NH₄-N L⁻¹). Sakar et al. [33] stated that ammonium ions are tolerated up to 1.5 g/L as NH₄-N, with CH₄ inhibition with NH₄-N concentrations above 4.9 g/L and 100% inhibition above 8 g/L. Ammonium toxicity can likely be avoided if optimal digester pH is maintained (6.8 to 7.2) and the ammonium-nitrogen concentration remains below 1.5 - 3 g L⁻¹ [34, 35], both of which were maintained in the full-scale PIH digestion system.

In addition, high pathogen removal rates were shown at the PIH digesters, with 99.9 and 99.95% reduction in total coliforms and *Escherichia coli*, respectively. Previous studies have also shown 99% and 97% reductions in total coliforms and *Escherichia coli*, respectively, with Taiwanese-model digester operated at 25°C using a 40-day retention time [29]. Kumar et al. [30] observed that when digesting cow manure *Escherichia coli* and *Salmonella typhi* survived up to 20 days at 18–25°C and 10 days at 35°C, *Shigella dysenteriae* survived up to 10 and 5 days, respectively, and *Streptococcus faecalis* survived the longest: 35 days at 18–25°C and 15 days at 35 °C. While 100% elimination was not achieved in the PIH system, *E. coli* levels of 1.40 CFU 100 ml⁻¹ were achieved in the effluent, which is less than the criteria for bathing waters in the US. The digesters

were not heated but were constructed using black geomembrane bags in order to absorb additional solar heat. The digesters had an average effluent temperature of 29.6 °C, which closely approximated the ambient temperature in Cange with mean January and August temperatures of 27.1 °C and 29.7 °C, respectively [31]. While pathogens were not eliminated, the VS and COD concentrations decreased by 96.0 and 98.5%, respectively, during digestion (Table 5). The COD concentrations were much less than predicted, likely due to the decreased amount of users (6.1 g L⁻¹) There was an 89.1 % increase in alkalinity, but the effluent pH (6.84) remained within the circumneutral pH range needed for effective CH₄ production.

4.0 Conclusions

This research illustrated the larger methane potential when sanitary waste was source separated using the DESAR concept for more appropriate treatment of each waste stream. The full-scale digestion CH₄ production was within the range of CH₄ production values predicted from the BMPs, confirming the ability of the BMPs to act as a prediction tool for full-scale digestion. While pathogen elimination was not achieved in the full-scale system, there was a 99.9% reduction in pathogens, 98.5% reduction in COD, and 0.1 m³ of biogas produced per day, with only 31 uses per day. As the number of users increases, there is a need for the on-going long-term monitoring of the full-scale system to determine how the increased usage will affect biogas production and treatment efficacy.

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Tables:

Table 1: The inoculum-substrate ratio (ISR) and cumulative CH₄ production for the four BMP tests are shown normalized by volatile solids (g VS added) and volumetric loading (ml of substrate). Values are given as averages of triplicate BMP bottles $\pm$ standard error, with cumulative CH₄ from the inoculum previously subtracted from each treatment.

Substrate Source	ISR Ratio (volume)	ISR Ratio (VS)	Cumulative CH ₄ (ml ml ⁻¹ substrate)	Cumulative CH ₄ (ml g ⁻¹ VS added)	CH ₄ (%)
BMP1: Latrine 1	6:1	1:2	7.5 $\pm$ 0.8	99.3 $\pm$ 10.4	46.2 $\pm$ 1.0
BMP1: Grey Water 1	1:25	2:1	0.02 $\pm$ 0.0003	38.6 $\pm$ 0.7	22.7 $\pm$ 0.7
BMP1: Dairy Manure	5:1	1:3	16.6 $\pm$ 0.2	151 $\pm$ 2	56.3 $\pm$ 0.4
BMP2: Latrine 2	4:1	1:4	21.3 $\pm$ 2.0	137 $\pm$ 17	68.5 $\pm$ 1.2
BMP2: Grey Water 2	1:2	2:1	0.5 $\pm$ 0.2	52.7 $\pm$ 18.4	28.0 $\pm$ 3.2
BMP2: Grey Water 3	1:2	10:1	< 0.001	52.9 $\pm$ 5.5	1.0 $\pm$ 0.1
BMP3: Latrine 1	2:1	1:2	11.6 $\pm$ 0.1	79.1 $\pm$ 0.5	67.6 $\pm$ 0.4
BMP3: Latrine 2	2:1	1:3	9.3 $\pm$ 0.6	43.4 $\pm$ 2.7	66.9 $\pm$ 0.4
BMP3: Grey Water 2	1:2	1:1	< 0.01	< 0.001	68.8 $\pm$ 0.3
BMP3: Grey Water 4	1:2	1:1	< 0.01	< 0.001	67.8 $\pm$ 0.4
BMP4: Latrine 1	9:1	1:1	18.5 $\pm$ 0.1	136 $\pm$ 1	65.4 $\pm$ 0.7
BMP4: Latrine 1*	9:1	1:1	17.8 $\pm$ 1.1	131 $\pm$ 8	64.8 $\pm$ 0.6
BMP4: Hospital Septage	1:1	1:1	0.6 $\pm$ 0.1	35.6 $\pm$ 4.3	55.6 $\pm$ 0.5
BMP4: Hospital Septage*	1:1	1:1	0.4 $\pm$ 0.01	22.7 $\pm$ 0.5	52.6 $\pm$ 0.6
BMP4: Grey Water 3	1:57	1:1	< 0.001	1.7 $\pm$ 1.0	5.0 $\pm$ 0.6
Avg. Latrine	-	-	13.6 $\pm$ 2.1	99.0 $\pm$ 16.6	62.9 $\pm$ 4.2
Avg. Septage Pit	-	-	0.58 $\pm$ 0.1	35.6 $\pm$ 4.3	55.6 $\pm$ 0.5
Avg. Grey Water	-	-	0.09 $\pm$ 0.07	24.3 $\pm$ 4.2	32.2 $\pm$ 12.1

*Indicates no nutrient media was added to these triplicate bottles.

Table 2: Characterization of the Haiti hospital complex waste sources for total solids (TS), volatile solids (VS), chemical oxygen demand (COD), and percent solids. Lower case letters represent significant differences from ANOVA and Tukey-Kramer analyses between substrates (within columns). Values are given as averages $\pm$ standard error.

Substrate	TS (g/L)	VS (g/L)	COD (g/L)	Solids (%)
Latrines	167 $\pm$ 17 ^a	133 $\pm$ 13 ^a	456 $\pm$ 79 ^a	16.3 $\pm$ 1.6 ^a
Hospital Septage	16.3 $\pm$ 6.7 ^b	12.3 $\pm$ 4.2 ^b	12.8 $\pm$ 5.0 ^b	1.6 $\pm$ 0.3 ^b
Grey Water	11.7 $\pm$ 3.1 ^c	6.8 $\pm$ 2.4 ^b	3.3 $\pm$ 0.5 ^b	1.0 $\pm$ 0.3 ^b
Dairy Manure	145 $\pm$ 3 ^a	110 $\pm$ 7 ^a	558 $\pm$ 7 ^a	15.0 $\pm$ 0.3 ^a
Dairy Digester Inoculum	15.9 $\pm$ 2.7 ^{bc}	9.2 $\pm$ 2.1 ^b	22.3 $\pm$ 2.8 ^b	1.7 $\pm$ 0.2 ^b
Wastewater Digester Inoculum	23.5 $\pm$ 0.2 ^b	15.9 $\pm$ 0.2 ^b	23.0 $\pm$ 0.2 ^b	2.4 $\pm$ 0.01 ^b

600 **Table 3:** Cumulative CH₄ production for the four BMPs normalized by volume (ml ml⁻¹ substrate) and volatile solids (ml g⁻¹ VS
601 added), utilizing percent CH₄ data from Day 10 to the end of each experiment. Lower case letters represent significant differences
602 within each column. Average values for each date ranges include all BMP values (BMP1 results included in average for Days 0-47
603 and Days 0-66 and BMP4 for Days 0-66).

604

Substrate	Cumulative CH ₄ (ml ml ⁻¹ substrate)			Cumulative CH ₄ (ml g ⁻¹ VS added)		
	Days 0 - 30	Days 0 - 47	Days 0 - 66	Days 0 - 30	Days 0 - 47	Days 0 - 66
BMP1: Latrine 1	7.5 ± 0.8 ^a	-	-	99.3 ± 10.4 ^{ac}	-	-
BMP1: Dairy Manure	16.6 ± 0.2 ^{bc}	-	-	151 ± 2 ^b	-	-
BMP1: Grey Water 1	0.02 ± 0.0003 ^{de}	-	-	38.6 ± 0.7 ^{cd}	-	-
BMP2: Latrine 2	17.1 ± 1.6 ^b	19.7 ± 2.0 ^a	21.0 ± 1.0 ^a	123 ± 11 ^{ab}	127 ± 13 ^a	137 ± 17 ^a
BMP2: Grey Water 2	0.5 ± 0.6 ^d	0.5 ± 0.2 ^b	0.5 ± 0.2 ^{bc}	50.5 ± 17.7 ^{cd}	50.5 ± 17.7 ^{bc}	52.7 ± 18.4 ^b
BMP2: Grey Water 3	< 0.001 ^d	< 0.001 ^b	< 0.001 ^b	52.7 ± 5.5 ^{cf}	52.9 ± 5.5 ^b	52.9 ± 5.5 ^b
BMP3: Latrine 1	10.6 ± 0.008 ^a	11.2 ± 0.08 ^c	11.6 ± 0.1 ^{ad}	72.3 ± 3.2 ^{adf}	76.6 ± 0.3 ^{ac}	79.1 ± 0.5 ^{ab}
BMP3: Latrine 2	8.8 ± 0.7 ^a	9.0 ± 0.6 ^c	9.3 ± 0.6 ^{cd}	41.0 ± 0.1 ^{cd}	42.1 ± 2.7 ^{bc}	43.4 ± 2.7 ^b
BMP3: Grey Water 2	< 0.001 ^d	< 0.001 ^b	< 0.001 ^b	< 0.001 ^e	< 0.001 ^d	< 0.001 ^c
BMP3: Grey Water 4	< 0.001 ^d	< 0.001 ^b	< 0.001 ^b	< 0.001 ^e	< 0.001 ^d	< 0.001 ^c
BMP4: Latrine 1	16.6 ± 0.02 ^c	18.5 ± 0.1 ^a	-	122 ± 0.2 ^{ab}	136 ± 1 ^a	-
BMP4: Grey Water 3	< 0.001 ^d	< 0.001 ^b	-	1.7 ± 1.0 ^c	1.7 ± 1.0 ^d	-
BMP4: H. Septage	0.46 ± 0.03 ^d	0.58 ± 0.1 ^b	-	28.4 ± 1.8 ^{cde}	35.6 ± 4.3 ^{bd}	-
Latrine Avg.	12.1 ± 1.2	13.2 ± 1.3	13.6 ± 2.1	91.5 ± 8.1	96.2 ± 10.9	99.0 ± 16.6
Grey Water Avg.	0.09 ± 0.07	0.09 ± 0.07	0.09 ± 0.07	23.9 ± 4.2	24.0 ± 4.2	24.3 ± 4.3

614

Table 4: Calculated CH₄ production values based on the highest (**H**) latrine CH₄ production (BMP2: 21.3 ml ml⁻¹ substrate) digested for 47 days and the lowest (**L**) latrine CH₄ production (BMP1: 7.5 ml ml⁻¹ substrate) digested for 30 days. The size of digester (m³) needed for 50-500 potential users is presented for each waste conveyance scenario based on a 47-day retention time.

Number of Users	Total fecal matter (m ³ d ⁻¹)	Calculated CH ₄ (m ³ d ⁻¹)	Latrine (no flush)	Latrine (0.5 L Bucket flush)	Low Flow Toilets (4 L)	Low Flow Toilets (4 L) with Urinal Diversion
m³ of Digester Needed: 47-day Retention Time						
50	0.06	H: 0.17; L: 0.06	1.2	2.4	9.2	6.3
100	0.016	H: 0.34; L: 0.12	2.4	4.8	18.5	12.5
300	0.048	H: 1.0; L: 0.36	7.1	14.3	55.4	37.5
500	0.080	H: 1.7; L: 0.60	11.8	23.9	92.4	62.6

621 **Table 5:** Wastewater characteristics for the full-scale AD System at PIH over a seven-month sampling period. Values are given as
622 averages $\pm$ standard error.

	TS^a (g L ⁻¹)	VS^b (g L ⁻¹)	COD^c (g L ⁻¹)	Total Coliforms (CFU ^d 100 mL ⁻¹)	<i>E. coli</i> (CFU ^d 100 mL ⁻¹)	Alkalinity (g CaCO ₃ L ⁻¹)	pH	Temperature (°C)
AD Influent	5.02 $\pm$ 1.01	4.21 $\pm$ 0.91	6.11 $\pm$ 0.85	11,000 $\pm$ 1470	2770 $\pm$ 567	0.260 $\pm$ 0.040	6.99 $\pm$ 0.16	29.4 $\pm$ 0.6
AD Effluent	0.33 $\pm$ 0.02	0.17 $\pm$ 0.03	0.092 $\pm$ 0.014	13.2 $\pm$ 2.46	1.40 $\pm$ 0.19	0.473 $\pm$ 0.037	6.84 $\pm$ 0.07	29.6 $\pm$ 0.2
% Reduction	93.4%	96.0%	98.5%	99.9%	99.95%	-81.9%*	2.1%	-0.4%*

^aTS: Total Solids; ^bVS: Volatile Solids; ^cCOD: Chemical Oxygen Demand; ^dCFU: Colony Forming Units; *negative values represent % increase

Figure Captions

Figure 1: The PIH anaerobic digestion system with latrine building, 3 cell AD system, and post-treatment wetlands.

Figure 2: Biochemical Methane Potential (BMP) results normalized by volume (ml CH₄/ml substrate) and volatile solids (ml CH₄/g VS) for latrine, septage and grey water. Only Grey W2 is shown, as all other grey water sources had negligible CH₄ production.

Figure 1

Figure 2A

A

Figure 2B

B