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Waste treatment and energy production from small-scale wastewater digesters

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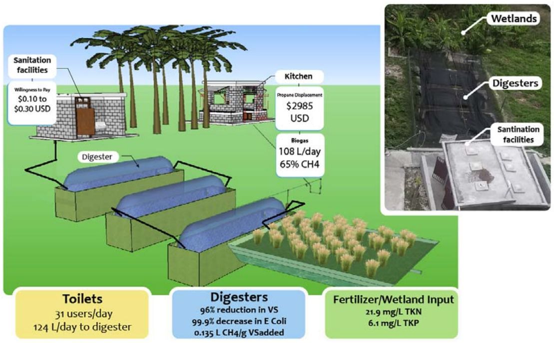
GRAPHICAL ABSTRACT



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ABSTRACT

Three tubular anaerobic digestion (AD) systems were installed in Haiti to treat black water (toilet-based wastewater), including a three cell 36 m^3 clinic digester (CD), a two cell 2 m^3 hotel digester (HD), and a three-cell 3 m^3 farm digester (FD) for worker use. During digestion, total coliforms were reduced by 99.1%, *E. coli* by 98.5%, and chemical oxygen demand (COD) by 93.6%. Nutrients in the effluent averaged 99.4 mg/L NH_4^+ and 10.6 mg/L PO_4^{2-}, producing an effective organic fertilizer. Average biogas production in CD was 108 L/d, with 65.4% CH_4. Survey participants (n = 573) were willing to pay $0.10–0.30 per use for sanitation facilities. Seventy-two percent of the rural population surveyed in Cange, Haiti lacked access to improved sanitation due to financial constraints. The economic analysis calculated an investment cost for a shared toilet AD systems of $16–$47 (USD) per person based on daily use at design capacity.

1. Introduction

An estimated 32% of the world population (2.4 billion people) do not have access to improved sanitation facilities, with 946 million people without access to any sanitation facilities (practicing open defecation) (WHO/UNICEF, 2015). Inadequate water, sanitation and hygiene practices resulted in 842,000 deaths in low and middle-income countries in 2012, equating to 1.5% of the global disease burden (WHO, 2014). 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 72% of the population without access to improved sanitation (WHO/UNICEF, 2015). The 2010 earthquake and on-going cholera outbreak highlighted the consequences of inadequate waste treatment, with 617,904 confirmed cholera cases and 5497 deaths due

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to cholera in Haiti, as of 14 January 2017 (MSPP, 2017). Feasibility studies revealed that construction, operation, and maintenance costs for centralized wastewater treatment would exceed the local capacity to pay (IADB, 2009). Additionally, wood and charcoal represent 70% of the energy use within the country, requiring approximately 25% of daily income; $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 (Delice et al., 2007), with charcoal and firewood burning for cooking estimated to shorten Haitian lifespan by 6.6 years (Smucker et al., 2007).

Past economic analyses of foreign investments in sanitation improvements in the developing world concluded that all possible investment scenarios were cost-beneficial, with a rate of return averaging $5–$28 (USD) for each $1 (USD) of sanitation investment (Haller et al., 2007). Dry and source-separated composting latrines have proven effective, and depending on the value of the compost, can yield economic returns (e.g. US$0.06/kg compost in Kenya; EcoSan, 2010). Isunju1 et al. (2013) detailed pay-for-use fee sanitary structures that have been successfully implemented elsewhere, with fees ranging from $0.03 to $0.11 (USD) per visit.

Anaerobic digestion (AD) for sanitation treatment has multiple distinct economic and health benefits: (1) energy recovery in the form of biogas, estimated at 22 MJ/m^3 biogas and 1.5 kg fuelwood displaced per m^3 biogas delivered; (2) air quality improvements during cooking; (3) greenhouse gas reductions; and (4) stabilization of the treated waste through large reductions in solids, pathogens, and odors, and the creation of a high nutrient soil amendment (Lansing et al., 2008a). Domestic wastewater treated using AD can produce 0.17 m^3 of methane (CH_4) per m^3 of wastewater (calculated from Berglund and Börjesson, 2006). Yet, the cost-effectiveness of AD systems is heavily dependent on construction quality, local material costs, and system lifetime.

Low-cost, non-mechanized AD designs, such as the plug-flow, Taiwanese-model digester, have successfully treated agricultural manure in Latin America and Asia with minimal energy inputs. In tropical climates, where mesophilic (20–35 °C) digestion can be maintained without heating, such AD designs have been shown to produce viable quantities of CH_4 and large reductions in organic waste (Lansing et al., 2008a; Ferrer et al., 2011). 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 (Vögeli et al., 2014). There are far fewer systems utilizing only human waste as the digestion input, largely due to the lower solids content, conveyance challenges, high nitrogen content of urine, and pathogenic concerns. There has been interest in using small-scale digesters to treat human waste for unserved populations (Nelson and Murray, 2008) and rural slums (Katukiza et al., 2010), as it was theorized that these systems could provide adequate sanitation and could prove to be more affordable to be local population.

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, economic analyses of these systems, and understanding of local population needs and desires, with regards to sanitation. The study objectives were to: (1) compare and contrast the treatment potential of three full-scale, low-cost AD sanitation-based systems, (2) determine the willingness to pay for sanitation facilities and the factors limiting their use, (3) determine the quantity and quality of biogas produced from the Haitian small-scale sanitation digesters and compare the biogas production to other small-scale digestion systems, and (4) conduct a financial analysis on the three AD systems and determine the financial viability of the AD systems in Haiti based on the willingness-to-pay survey results.

2. Materials and methods

2.1. Anaerobic digestion (AD) systems description

The three digesters were prefabricated using low-density polyethylene (LDPE) geomembrane tubular digesters with a 1.5 mm thickness (Sistema Biobolsa®, Mexico City, Mexico). All three systems received dairy manure as inoculum prior to receiving wastewater. The clinic digester (CD) system located in Cange, Haiti (18°56′06.6″N; 71°59′35.4″W) is a three-cell, 36 m^3 AD system with post-treatment subsurface wetlands (28.4 m^3) designed to receive black water from four low-flush toilets (using 4 L of conveyance water per flush) from 30 to 500 visitors per day. Each digester bag has a liquid phase of 12 m^3, with 10 m^3 of combined gas space within the three-cell AD system. The post-treatment wetland has a gravel substrate with a void volume of 0.5, creating an effective treatment volume of 14.2 m^3. Urinal waste and sink grey water are conveyed directly to the post-treatment wetlands to reduce flush water and nitrogen concentration in the digestion system. The AD design was based on biochemical methane potential (BMP) tests and feces analyses detailed in Lansing et al. (2016).

The hotel digester (HD) system is located in Port-au-Prince, Haiti (18°34′26.9″N; 72°16′54.3″W) and consists of 2 m^3 liquid volume and 1.2 m^3 combined gas storage between two interconnected digester bags fed by a flush toilet (using 4 L of flush water) inside a wooden structure with a sink. The system was designed for 20 to 50 uses per day. The used drainage water from the sink serves as the flush water for the toilet. Post-treatment consists of soil infiltration with a lined seepage pit, followed by an unlined seepage zone planted with banana trees. A portion of the effluent is collected prior to post-treatment and used in local gardens as a fertilizer.

The third AD system, a farm digester (FD), is located in Corporant, Haiti (18°53′25.2″N; 72°04′58.9″W) and receives waste from approximately 5 to 10 farm workers per day. The system is a three-cell AD system with a combined liquid volume of 3 m^3 and gas storage of 1.8 m^3, receiving waste from one flush toilet and sink water. After digestion, the effluent is used directly in surrounding agricultural fields as a fertilizer. The FD system was installed during a two-day AD workshop by the Haitian participants.

2.2. Wastewater sample characterization and statistical analyses

Samples were collected from the influent and effluent pipes of each digester during normal operation over seven sampling events during a seven-month period. Samples were analyzed in triplicate at the Laboratoire de Qualité de l'Eauau et de l'Environnement at Université Quisqueya in Haiti, with additional samples collected and transported on ice within two days of collection from Haiti to the Water Quality Laboratory at the University of Maryland in College Park, MD, USA and stored at 4 °C for analysis. All samples were analyzed for pH, COD, total solids (TS), volatile solids (VS), alkalinity, total coliforms, and *Escherihia coli (E. coli)*, according to Standard Methods (APHA et al., 2005). Samples from the HC and CD systems were analyzed in the US for volatile fatty acids (VFAs: acetic, propionic, *n*-butyric, and *n*-valeric acids) using a HP 7890A gas chromatograph. A Lachat Automated Ion Analyzer (QuickChem 8500 Series 2 FIA) was used to determine ammonia, orthophosphate (PO_4^{3-}), total Kjeldahl nitrogen (TKN), and total Kjeldahl phosphorus (TKP). Ammonia samples were acidified to a $pH < 2$ with 5 N H_2SO_4, then filtered through 0.45 μm nitrocellulose membrane and analyzed using Lachat QuikChem Method 10-107-06-2-O. Orthophosphate samples were filtered through 0.45 μm membrane filters and analyzed using QuikChem Method 10-115-01-1-V. Samples analyzed for TKN (QuikChem Method 13-107-06-2-D) and TKP (QuikChem Method 13-115-01-1-B) were Kjeldhal digested with concentrated H_2SO_4 and $CuSO_4 * 5H_20$ before analysis on the Lachet. Total coliforms and *E. coli* were quantified using a pour plate method adapted to determine bacteria density in concentrated samples with high