ABSTRACT

Title of document: ENVIRONMENTAL SUSTAINABILITY AND WASTE TREATMENT CAPABILITIES OF SMALL-SCALE ANAEROBIC DIGESTION SYSTEMS

Andrew Robert Moss, Master of Science, 2012

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Anaerobic digestion is a common form of waste treatment and energy production throughout the world, and in the United States the number of agricultural digesters is increasing at a rate of approximately 10% annually. As the number of digesters grows, efforts to assess the environmental cost of their installation and the potential utility of their by-products are required. This research investigates the relative environmental sustainability of small-scale digesters treating dairy manure in the U.S. and human waste in Haiti, and explores the biogas potential and nutrient transformations resulting from the anaerobic digestion of dairy manure. Specifically, the objectives of the research are: 1) to conduct an eMergy analysis on the two digestion systems to assess the effect of waste source, climate, and infrastructure on system sustainability; and 2) to provide an overview of waste treatment and energy production options for agricultural digesters treating dairy manure in the United States.

ENVIRONMENTAL SUSTAINABILITY AND WASTE TREATMENT CAPABILITIES OF SMALL-SCALE ANAEROBIC DIGESTION SYSTEMS

By

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Thesis submitted to the Faculty of the Graduate School of the
University of Maryland, College Park, in partial fulfillment
of the requirements for the degree of
Master of Science
2012

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ACKNOWLEDGEMENTS

This work was supported by the USDA Sustainable Agricultural Research & Education (SARE) program, and funded by the Maryland Water Resources Research Center and University of Maryland Agriculture Experiment Stations. I would like to thank Dr. David Tilley and Dr. Walter Mulbry for their scientific guidance throughout the many phases of my time at the University. Additionally, I'd like to thank Gary Seibel and the ENST shop for their technical guidance and engineering expertise during construction and installation of the various components of both the Haitian and Maryland anaerobic digestion systems. Jon Leith, Mike Kemp, Brad Green, Keith Hummell, and the rest of the crew at the USDA Beltsville Agricultural Research Center provided hundreds of hours of often unsolicited help and guidance that were indispensable to the construction of the Maryland digesters. Additional thanks are due to the Lansing Lab Group including Faaiz Ajaz, Scott Allen, Grant Hughes-Baldwin, Ashley Belle, Holly Bowen, Kyla Gregoire, Anisha Gupta, Kayoko Iwata, Caiti Jackson, PJ Klavon, Sol Lisboa Kotlik, Akua Nkrumah, Ryan Novak, Owen Williams, Freddy Witarsa, Veronika Zhiteneva, and special thanks to my partner and cohort Katherine Klavon for her hard work, dedication, patience, and unique perspective throughout the various phases of the project.

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1.1 What is Digestion?

Anaerobic digestion – the microbial degradation of organic matter to carbon dioxide and methane in the absence of oxygen – is a process used globally as a tool for waste treatment and energy production, and it is often suggested as a component of future waste management systems in the United States (AgSTAR, 2006). More than 30 million operational digesters currently exist in China, 4 million in India, 10,000 in Latin America, 9,400 in Europe, 2,200 in Africa, and 880 in Canada and the United States (AgSTAR, 2012; Burns, 2009; IEA, 2011; Mshandete and Parawira, 2010; USEPA CHP Partnership, 2011). These systems vary both in terms of scale – with more small-scale systems in Asia, Africa, and Latin America – and in digestion substrate, which ranges from the organic component of municipal solid waste to agricultural manures.

The anaerobic digestion of organic materials proceeds through four fundamental chemical and biochemical stages within an anaerobic digestion system: 1) Hydrolysis - the extracellular, enzymatic degradation of carbohydrates, lipids, and proteins by facultative and obligate anaerobes to create soluble sugars, long-chain fatty acids (LCFAs), and amino acids that can be absorbed through their cell walls; 2) Acidogenesis and acetogenesis – the further degradation of sugars, LCFAs, and amino acids via fermentation into volatile fatty acids (VFAs), acetate, alcohols, ammonia, carbon dioxide, and hydrogen; and 3) Methanogenesis – the creation of methane and carbon dioxide from the products of acidogenesis and acetogenesis by obligate anaerobic Archaea known as methanogens (Ciborowski, 2001; Gavala et al., 2003; Gerardi, 2003). In practice, these microbial processes occur simultaneously in the anaerobic digestion environment, with numerous bacterial species carrying out one or multiple roles. As a whole, anaerobic digestion results in the breakdown of volatile organic solids (VS) and the creation of biogas, with reductions of 20-65% VS and biogas production of 0.75–1.0m^3/kg VS generally expected at mesophilic temperatures, depending on the type of waste (Ciborowski, 2001; Gerardi, 2003; Lusk, 1998).

1.1.1 The Anaerobic Digestion Process

1.1.1.1 Hydrolysis

At mesophilic temperatures, the hydrolysis of organic matter fed into an anaerobic digester involves the enzymatically-facilitated breakdown of complex polymeric organic compounds into the smaller, more soluble products of amino acids, glycerol, and fatty acids (often termed long-chained fatty acids, or LCFAs) (Gerardi, 2003; Mackie et al., 1991). Hydrolytic fermentative bacteria – facultative and obligate anaerobic bacteria that are also termed acidogenic bacteria due to the fatty acids produced during the hydrolysis process – are responsible for the process, and it occurs independently of the rate of bacterial growth via first-order kinetics (Gavala et al., 2003; Masse et al., 2002). An example of hydrolysis in the anaerobic digestion process is the degradation of triglycerides into glycerol, which is catalyzed via the extracellular enzymatic activity of lipase (Figure 1-1) (Masse et al., 2002):

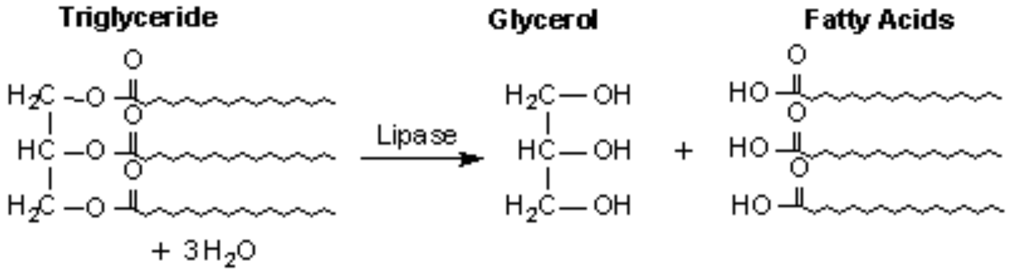


Figure 1-1 - The enzymatic hydrolysis of triglycerides to glycerols and LCFAs. Adapted from O'Mahony and Peters (1987).

1.1.1.2 Acidogenesis/Acetogenesis

Acidogenesis is a fermentative process which degrades the products of hydrolysis primarily to 1,3-propanediol and acetic acid in an approximate 1:2 ratio, with minimal byproducts, such as 2,3-butanediol, ethanol, CO_2 and H_2O, also formed (Biebl et al., 1998; Yazdani and Gonzalez, 2007). The literature suggests that the pathway for acidogenesis involves the dehydration of glycerol by dehydratase to form 3-hydroxypropionaldehyde, which is then reduced to 1,3-propanediol by the NADH-linked 1,3-propanediol dehydrogenase, which accomplishes the reoxidation of NADH to NAD^+ (Booth, 2005; Yazdani and Gonzalez, 2007). Following this dehydration/reduction reaction, the 1,3-propanediol molecule finds its way into the acetogenic β-oxidation process, eventually leading to the production of additional acetate and H_2 (Jeganathan et al., 2006). The acetic acid, hydrogen, and carbon dioxide resulting from the acidogenic phase are used directly in the last step of the digestion process – methanogenesis; all other by-products continue on into the acetogenic phase of the process (WtERT, 2009).

Acetogenesis occurs as the remaining by-products of hydrolysis – primarily alcohols and LCFAs such as propionic and butyric acid – are utilized as a carbon source by acetogenic bacteria (Gavala et al., 2003; WtERT, 2009). During the breakdown of oils and fats, for example, LCFAs are adsorbed onto the surface of the bacterial cell wall which stimulates the production of the acyl-CoA synthetase enzyme by the microorganisms, in turn activating the breakdown of LCFAs via β-oxidation (Rinzema et al., 1994; Salminen and Rintala, 2002).

$$CH_3(CH_2)_8COOH + 2H_2O \rightarrow CH_3(CH_2)_6COOH + CH_3COOH + 2H_2$$

This reaction has been proffered as one of the most probable limiting steps in the overall AD process, as incomplete degradation of LCFAs to the end-products negatively influences further reactions in the AD process (Broughton et al., 1998; Chen et al., 2008; Masse et al., 2002).

1.1.1.3 Methanogenesis

Methanogenesis is a term used to describe the production of methane from methanogens, evolutionarily primitive bacteria that are members of the domain, Archaebacteria (Gerardi, 2003). As a general rule, methanogenic bacteria can produce methane through the utilization of a limited number of chemical substrates: CO_2, acetate (CH_3COO^-), and methyl-group containing compounds, using H_2, formate ($HCOO^-$) and, in a limited number of instances, secondary alcohols and carbon monoxide, as electron donors (Gerardi, 2003; Liu and Whitman, 2008; Thauer, 1998). Many methanogens are hydrogenotrophs that have the ability to reduce CO_2 to CH_4 using H_2 as the primary electron donor (Gerardi, 2003):

$$CO_2 + H_2 \rightarrow CH_4 + H_2O$$

In this process, H_2-reduced ferredoxin – an iron-sulfur protein produced by the microbes for mediation of electron transfer – donates electrons in a reaction binding CO_2 to methanofuran to create a formyl group (Liu and Whitman, 2008). The newly generated formyl group is then transferred to the coenzyme tetrahydromethanopterin ($C_{30}H_{45}N_6O_{16}P$), forming formyl-tetrahydromethanopterin. The formyl group is dehydrated to a methenyl group, reduced to methylene-tetrahydromethanopterin using the coenzyme F_{420} as the electron donor, and reduced again to methyl-tetrahydromethanopterin using the same coenzyme. At this point, the methyl group is transferred to Coenzyme M (CoM), and then reduced to CH_4 by the enzyme methyl CoM reductase using electrons donated from Coenzyme B (CoB). The oxidized CoB then binds with the CoM enzyme to form a heterodisulfide:

$$CH_3\text{-S-CoM} + \text{H-S-CoB} \rightarrow \text{CoM-S-S-CoB}$$

which is subsequently reduced, generally using H_2 as an electron donor, to reestablish the active thiol sites of each molecule (Liu and Whitman, 2008; Thauer, 1998). This reduction is also where the methanogens derive their energy, as the reduction of the heterosulfide using dehyrogenase and heterodisulfide reductase has been shown to couple to the phosphorylation of ADP to form ATP (Liu and Whitman, 2008; Thauer, 1998). Surprisingly, although there are several chemical analogues produced by different species during the methanogenic process, the essential mechanics remain the same amongst all hydrogenotrophic bacteria (Liu and Whitman, 2008; Thauer, 1998).

In acetotrophic/aceticlastic methanogens, the use of acetate as a substrate for methane production occurs through a variation of the same mechanism seen in hydrogenotrophic methanogenesis, although the two genera of bacteria responsible for the process (*Methanosarcina* and *Methanosaeta*) carry it out in different ways (Liu and Whitman, 2008; Thauer, 1998). The basic outline of the conversion is as follows (Gerardi, 2003):

$$4CH_3COOH \rightarrow 4CO_2 + 2H_2 \rightarrow CH_4 + H_2O$$

The *Methanosaeta* genus uses energy from the hydrolysis of ATP to adenosine monophosphate (AMP) to activate acetate to acetyl-CoA using AMP-forming acetyl-CoA synthetase. The genus *Methanosarcina* uses energy from the hydrolysis of ATP to inorganic pyrophosphate to create acetyl-CoA using a combination of acetate thiokinase and phosphotransacetylase (Liu and Whitman, 2008; Smith and Ingram-Smith, 2007). At this point, the actetyl-CoA is either oxidized to CO-S-CoA by ferredoxin to produce H_2, CO_2, and a reformed CoA enzyme (at which point the conversion of the products to CH_4 continues under the hydrogenotrophic methogenesis pathway), or it is transferred to the coenzyme tetrahydromethanopterin, where it follows the same process of methanogenesis as seen in hydrogenotrophic bacteria (Liu and Whitman, 2008; Smith and Ingram-Smith, 2007). The acetoclastic pathway for methanogenesis typically accounts for greater than two-thirds of all methane produced during anaerobic digestion (Gavala et al., 2003; Jones, 1991; Mountfort and Asher, 1978; Zinder et al., 1984).

1.1.2 Inhibitions to Anaerobic Digestion

In practice, hydrolysis, acidogenesis/acetogenesis, and methanogenesis do not occur in the distinct stages presented above but are instead ongoing, with generated substrates and byproducts greatly influencing the rates and mechanics of each process. This has important implications on the efficiency of converting organic matter to methane and, therefore, on the net energetics of the AD system. Because methane generation for energy production is frequently the desired outcome of anaerobic digestion, these interactions are best discussed in the context within which they disrupt this process.

1.1.2.1 Long Chain Fatty Acid (LCFA) Inhibition

There is an abundance of research that supports the presence of inhibitory affects of LCFAs on methanogens, especially the acetotrophic bacteria (Hanaki et al., 1981; Jeganathan et al., 2006; Rinzema et al., 1994; Warren et al., 2003). As fats and oils undergo hydrolysis, large volumes of LCFAs can be introduced into the microbial community in a short period of time, both via hydrolysis and through the incomplete β-oxidation of other LCFAs (Carballa and Vestraete, 2010; Rinzema et al., 1994). LCFAs can negatively influence the production of methane by aceticlastic and hydrogenotrophic methanogens, occasionally permanently disabling the production of methane in the AD system (Cirne et al., 2007). Some researchers have proposed that the mechanics for this particular inhibition is due to the chemical and structural similarities of several LCFAs to the lipid components of the cell wall of methanogens. They suggest that these similarities allow the LCFAs to be absorbed into the cell wall structure where they inhibit the transfer of molecules into the cell, thereby disrupting normal enzymatic and catabolic activity (Gerardi, 2003; Rinzema et al., 1994). LCFAs may also inhibit the hydrolysis process due to the specificity of lipases, which generally require a cellular interface for activation (Cirne et al., 2007). There is some debate as to whether these inhibitions are more directly related to the LCFA:biomass ratio (Hanaki et al., 1981) or to the overall concentration of LCFAs in solution (Rinzema et al., 1994), but its overall significance to the AD process is not in question. Additionally, the adsorption of LCFAs to biomass leads to flotation of the anaerobic digester's sludge substrate, which causes a subsequent washout of the system (Rinzema et al., 1989). This leads to a short-circuiting of the AD system, a decrease in the efficacy of waste treatment, and a reduction in overall CH_4 production (Chen et al., 2008).

1.1.2.2 Low pH Inhibition

Decreases in pH within the AD system may occur for a variety of reasons, the most obvious of which is the production of acidity via the β-oxidation of LCFAs (Gerardi, 2003). In a stable AD system, this increase in acidity is offset by the utilization of acetate by the methanogenic population, with which acetogenic bacteria share a symbiotic relationship. If methanogenesis via the aceticlastic bacteria is inhibited (during excessive production of LCFAs, for example), both hydrogen and acetate begins to build in the system, and pH begins to drop. A drop in acidity and an accompanying increase in the partial pressure of H^+ in the system can reduce acetotrophic methanogen, as they are themselves inhibited by increasing acidity (Gerardi, 2003). This, in turn, inhibits acetogenic bacteria, as high H^+ partial pressure inhibits their metabolism. Acetogens reproduce slowly (generation times > 3 days), and the AD system may therefore take time to restabilize. These problems are compounded by the addition of non-lipid substrates to the digester, which are degraded by different bacteria with different resulting products, such as butyrate and propionate, which contribute large amounts of acidity to the system (Angelidaki and Ahring, 1997; Chen et al., 2008; Gerardi, 2003; Jarvis et al., 1999). Inhibition of methanogenesis due to interference in enzymatic activity can occur at pH levels as high as 6.8, and there are very few methanogens that can efficiently metabolize at pH values less than 6.2 (Gerardi, 2003; Thauer, 1998). These relatively low H^+ concentrations and their significant effect on the methanogenic population underscores the significance of pH on the AD process.

1.1.3 The Ecology of Methanogens

The organisms found in anaerobic digestion systems represent a large consortium of microbes that include, based on changes in the physical and chemical conditions within the digester, the domains Fungi (yeasts, in this case), Protists, Eubacteria, and Archaeabacteria (Toerien and Hattingh, 1969; Gavala et al., 2003). At a phenotypic level, bacteria and methanogens can be differentiated in a number of ways. First and foremost, methanogens are the only bacteria that produce methane. Secondly, although both groups consist entirely of prokaryotic, single-celled microorganisms that lack a true nucleus and membrane-enclosed organelles, the methanogens' cell wall and cell membrane structures do not contain the peptidoglycan characteristic of other prokaryotic bacteria (Kandler and König, 1998), but instead possess lipids composed of isoprenoids that are ether-linked to glycerol or carbohydrates, leading to the problematic interactions with LCFAs mentioned earlier (Lai et al., 2008).

The anaerobic digestion of organic matter is carried out by the concerted action of bacteria representing the three trophic stages of the process: hydrolytic fermentative bacteria, syntrophic acetogenic bacteria, and methanogens (Gerardi, 2003; Stams and Plugge, 2010). In the hydrolysis stage of AD, Eubacteria such as *Bacterioides*, *Clostridium*, and *Streptococcus* are active in lipid-containing systems and are almost entirely responsible for the breakdown of the original triglyceride substrates into the simpler molecules utilized by methanogens (Liu & Whitman, 2008; Gerardi, 2003). The acetogenic process is generally dominated by fermenting bacteria like *Clostridium* or fatty-acid oxidizing bacteria like *Syntrophomonas*, and these species are syntrophically-linked to hydrogenotrophic methanogens due to a H^+ inhibition that interferes with metabolic activity (Lee and Zinder, 1988). Some research has suggested that the lypolytic/glycerol-fermenting bacteria actively degrading LCFAs at this trophic level may have developed a resistance to elevated levels of LCFAs, indicating that these bacteria may metabolize at a more continual rate than the majority of other bacteria in the system, providing another reason for the high H^+ partial-pressure forcing that is associated with pH inhibitions (Jarvis et al., 1999).

Methanogens have been divided into five orders: *Methanobacteriales*, *Methanococcales*, *Methanomicrobiales*, *Methanopyrales*, and *Methanosarcinales* (Thauer, 1998). Of these, only *Methanosarcinales* and, within this order, the genus *Methanosarcina* and *Methanosaeta*, are known to use acetate, the major product of triglyceride hydrolysis and fermentation, as a substrate for methanogenesis (Liu & Whitman, 2008). Amongst the factors affecting the growth of these groups, temperature is the most important. Most AD industrial processes operate in the mesophilic (25º - 40ºC) and thermophilic (45º – 60ºC) ranges, although methanogens have differing optimal growth conditions – some can grow at psychrophilic conditions (0º - 20ºC) and others at near 100ºC (Boone et al., 1993), and methane production exhibits a broad spectrum of Q_{10} values ranging as high as 30-40 (Q_{10} values describe the temperature dependence of chemical and biological reactions; most biological systems have a Q_{10}

value between 2 and 3) (Sadava et al., 2009; Sylvia et al., 2004). Biologically, one of the largest obstacles to overcome in commercialized AD in the United States is the adaptation of a methanogenic population to cold temperatures/climates. Some methanogens from the order *Methanomicrobiales* have shown promise in adapting to and thriving in these conditions, although little is known about them (O'Reilly et al., 2009).

As the degradation of organic substrates progresses via the metabolic processes of all AD microorganisms, several interactions are of interest when considering the general stability of the system. The first is the interspecies transfer of fermentation products, such as hydrogen (Thiele and Zeikus, 1988). Acetotrophic bacteria reproduce more slowly than hydrogenotrophic methanogens, and this difference in growth rates and catabolic activity often leads to a natural build-up of H^+ and other acidic end-products in an AD system and a partial uncoupling of the AD reactions (Gerardi, 2003; Stams and Plugge, 2010; Thiele and Zeikus, 1988). This accumulation of H^+ and acidic conditions normally promotes the thermodynamic favorability of methanogenesis over acetogenesis by hydrogenotrophic methanogens and an accompanying rate decrease in acetogenic activity. However, in high H^+ partial pressure environments, the evolutionary co-dependence of acetogenic and hydrogenotrophic methanogens appears to have enabled a mechanism for continued growth, as electron transfers (termed "interspecies H_2 transfer") from syntrophic acetogens to hydrogenotrophs has been shown to occur (Thiele & Zeikus, 1988). This type of interaction highlights the complex inter-relatedness of AD biological syntrophy.

The consortia of microorganisms within an anaerobic digester also exhibit the tendency to amalgamate into granular biofilms – groups of microbes representing both the Archaea and Bacteria domains that self-flocculate to form dense, suspended clusters in the liquid waste solution ranging in diameter from 0.2 to 5mm (Díaz et al., 2006; O'Reilly et al., 2009). Díaz et al. (2006) suggested that in the early stages of granular biofilm development, the gram-negative proteobacteria were generally the first to populate organic particulates. Soon thereafter, the domain Archaea become active, forming syntrophic associations with the bacteria already present. In these young granules, microbe populations are active and, therefore, reported to be compact and dense (Díaz et al., 2006).

As these granules age, most of the bacterial growth occurs at the external interface between granule and waste solution, and the granules become multilayered (Díaz et al., 2006). The microbiologically active exterior allows for degradation of substrates from the surrounding solution by hydrolytic and acetogenic/acidogenic bacteria while, via syntrophic relationships, methanogens tend to propagate internally causing the formation of large, multi-species colonies with high methanogenic activity dominated by the genus *Methanosaeta* (Díaz et al., 2006; Harmsen et al., 1996; Hulshoff Pol et al., 2004; O'Reilly et al., 2009); these observations seem to align well with the high ratios of acetate-derived methane calculated by Mountfort and Asher (1978) and Jones et al. (1991). Bacteria belonging to the genera *Syntrophomonas* and *Syntrophus* are known for their ability to grow on LCFAs in syntrophy with methanogens (Stams and Plugge, 2010), and may play a role in biofilms generated in high-lipid waste. Díaz et al. (2006) report that as the biofilm colonies age and the successive layers of microbes die out, the slow dissolution of the biofilm begins and empty spaces devoid of microbes and other substrates appear. *Methanosaeta* also dominates this stage, which fits well with reports of high concentrations of the genus in late-stage batch reactor systems (Malakahmad et al., 2009).

1.2 Types of Anaerobic Digesters

Anaerobic digesters are airtight, oxygen-free containers used to generate biogas from the microbial breakdown of organic wastes. They can be constructed from any number of different materials designed using many methods, but the most simple construction is a closed container filled with liquefied waste and closed to the external environment (Figure 1-2). The level of digester complexity varies depending on variables such as climate, capacity, feedstock, desired treatment times, required pathogen destruction, and cost-benefit analysis.

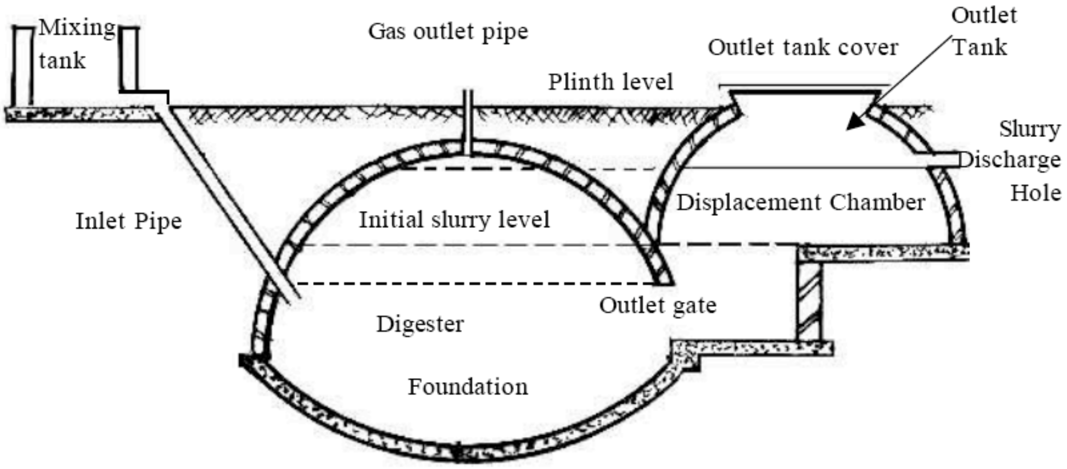


Figure 1-2 - A typical Indian fixed-dome anaerobic digester. The system is closed, but air from the slurry discharge hole can still enter the digester. By filling the main chamber with waste up to the initial slurry level, even this small amount of air can't reach the majority of the waste, and the digester quickly becomes anaerobic, or oxygen free. (Diagram credit: Action for Food Program, 2000)

1.2.1 Complete Mix or Continuously Stirred Tank Reactors (CSTRs)

Complete Mix digesters or continuously stirred tank reactors (CSTRs) are generally cylindrical containers made of fiberglass, steel or reinforced concrete and may be built above ground or partially buried (Kramer, 2009; Scott et al., 2010). In temperate climates, CSTRs are usually insulated, and the digestion chamber is heated with internal hot water piping and/or internal and external heat exchangers such as combined heat and power (CHP) electric generators (Kramer, 2009; Pennsylvania State University, 2008a; Scott et al., 2010). CSTRs are usually designed for operation in mesophilic or thermophilic temperature ranges (De Baere and Mattheeuws, 2008; Kramer, 2009; Scott et al., 2010).

The total solids contents of these digesters generally ranges from 2-5%, although they are often used for both scraped and washed manure management systems (Kramer, 2009; Scott et al., 2010). Similar to other digestion designs, sand bedding will settle out in the digester and should be separated prior to digestion (Burke, 2001; Wilkie, 2005). As the CSTR name implies, the reactors are constantly mixed via pumps, electric propellers, or pressurized biogas agitators in order to keep the solids portion of the waste in suspension and prevent settling. The waste is usually digested for 10-30 days (the hydraulic retention time, or HRT) before being pumped to a solids separator to remove the undigested material, such as bedding (Kramer, 2009; Scott et al., 2010). The remaining waste is often pump or gravity-fed to storage lagoons for later use as a crop fertilizer. Biogas generated during the process is captured under the airtight dome of the digester and may be scrubbed and used immediately for heating, electricity generation, vehicle fuel, etc., or compressed for storage.

1.2.2 Plug Flow

Plug flow anaerobic digesters are most often constructed as buried, reinforced concrete, fiberglass, or steel tanks, with a 5:1 length to width ratio, and are covered with a gas-tight flexible geo-membrane material similar to a pond-liner (Pennsylvania State University, 2008b; Scott et al., 2010). Similar to CSTRs, piped hot water and/or heat exchangers are combined with insulation to keep the digesters warm in temperate climates (Scott et al., 2010). Plug flow systems are typically operated at mesophilic or thermophilic temperatures.

Plug flow digesters are designed for high-solids waste streams (usually 10-15% total solids) (Wilkie, 2005), and ideal for scraped manure management systems. As with CSTRs, sand bedding must be settled out before being introduced to the digester (Burke, 2001; Wilkie, 2005). In theory, waste enters the system as a plug, flowing into one end and progressively moving through the digester as new waste is introduced. After the designed HRT – normally ranging from 15 to 30 days (Burke, 2001; Wilkie, 2005) – the plug is pushed out as effluent and drained to a holding lagoon. Although mixing is not theoretically required in plug flow systems, in practice, many designers and owners agitate to avoid manure crusting and short-circuiting of the system. To that end, plug flow digesters may incorporate some of the stirring aspects of CSTR digester designs.

1.2.3 Covered Lagoon

Covered lagoon digesters are often retrofits of existing manure lagoons and may be operated as a combined digester and waste storage lagoon or split into two or more single-function units (NRCS, 2006; Westerman et al., 2008). They consist of a holding basin, often constructed using pond-lining materials, and a fixed or floating impermeable membrane cover. Covered lagoon digesters operate at ambient temperatures and, in colder climates, this can result in lower biogas production when compared to heated systems (Pennsylvania State University, 2008c).

Covered lagoon digesters are designed for low solids waste streams (<2% total solids), and generally require pre-separation of the solid constituents of the manure (Pennsylvania State University, 2008c; Wilkie, 2005). Waste is pumped or gravity-fed to the digester in a manner similar to most plug flow systems and, due to lower operating temperatures, HRTs range from 35 to 60 days (NRCS, 2006; Pennsylvania State University, 2008c; Wilkie, 2005).

1.2.4 Fixed Film

Fixed film digesters are constructed in a similar method to CSTR digesters, but with several key differences (Wilkie, 2000), including inclusion of non-degradable, high surface area material inside of the digester as a growth media for the anaerobic microbes. The material types and designs are variable – the University of Florida's fixed film research digester, for example, uses sections of vertically stacked 3-inch corrugated plastic pipe (Wilkie, 2000) – but the fundamental purpose is to increase the density of the microbial population, leading to reduced HRTs and smaller digester volumes. As with CSTRs, these systems operate at mesophilic or thermophilic temperatures (Pennsylvania State University, 2008d; Wilkie, 2005).

Similar to covered lagoon systems, fixed film digesters are designed for low solids waste streams (<2% total solids) and require sand-settling or screen separation of bedding prior to digestion (Wilkie, 2005). The liquid waste is designed to move through and around the fixed media, and usually flows from bottom to top (upflow) or top to bottom (downflow). HRTs range from 3-5 days, after which the waste and biogas are handled in the same fashion as other digestion systems (Pennsylvania State University, 2008d; Wilkie, 2005).

1.2.5 Cost

Digester capital costs vary greatly according to a number of factors, including the required treatment capacity, local climate, desired operating temperature, type of waste stream, intended use of biogas, and many other factors unique to each farm. A brief compilation of capital costs per cow for dairy farms is provided below (Table 1-1), including information on the state of operation for each system included.

Table 1-1 - Average Capital Costs for Anaerobic Digesters on U.S. Dairy Farms in 2011 Dollars.

Digester Type	Avg. Cost per cow	Avg. farm size (# cows)	Electricity Generation	# Projects Counted [Built, (Projected)]	Source
Covered Lagoon	$2,175	100	No	0, (1)	a
Covered Lagoon	$844	495	Yes	1, (2)	a, b
Plug Flow	$1,369	150	No	1, (2)	a
Plug Flow	$2,224	120	Yes	1, (0)	a
Complete Mix	$1,466	173	No	2, (1)	a
Complete Mix	$1,963	180	Yes	2, (0)	a
Fixed Film	$1,503	175	No	2, (0)	a
Fixed Film	$1,184	625	Yes	0, (2)	b

a) (Klavon, 2011); b) (Giesy et al., 2005)

1.2.6 Emerging Designs for Small-Scale Farms

1.2.6.1 Modified Taiwanese Plug-flow Bag Digesters

Taiwanese bag digesters are common throughout the world, but especially in Latin America, where they are often used to treat dairy and swine manure (Burns, 2009; Lansing et al., 2010; Vízquez Arias, 2009). The mechanics of these digesters are similar to traditional U.S. plug-flow designs but the construction materials differ. Most Latin American bag digesters are directly buried in the ground, where the digester bag (often a PVC or polyurethane-based material) is attached to influent and effluent plumbing, inflated, and filled to capacity.

The University of Maryland has begun efforts to adapt this particular design to the temperate climates of the United States. Dual- walled, corrugated high-density polyethylene culverts are buried to provide insulation, and house typical Latin American bag digesters, with insulation and radiant hot water piping added to further maintain heat. The plug-flow digesters are designed for high-solids waste streams (10-15%), but operate on pre-separated liquid manure, as well. Dairy manure is pre-heated using biogas and gravity-fed to the digesters in a manner similar to other plug-flow designs, where it is maintained at mesophilic temperatures. Periodically, the effluent of the system is pumped to the front of the digestion system, re-heated and recirculated into the system to maintain digestion temperatures and a healthy microbial community throughout the digester. Effluent and biogas are handled in a manner identical to standard digestion systems.

As an alternative to biogas-generated hot water for digester heating, solar hot water has been used in some systems. No biogas production values from these systems are currently available, so their viability is still unknown.

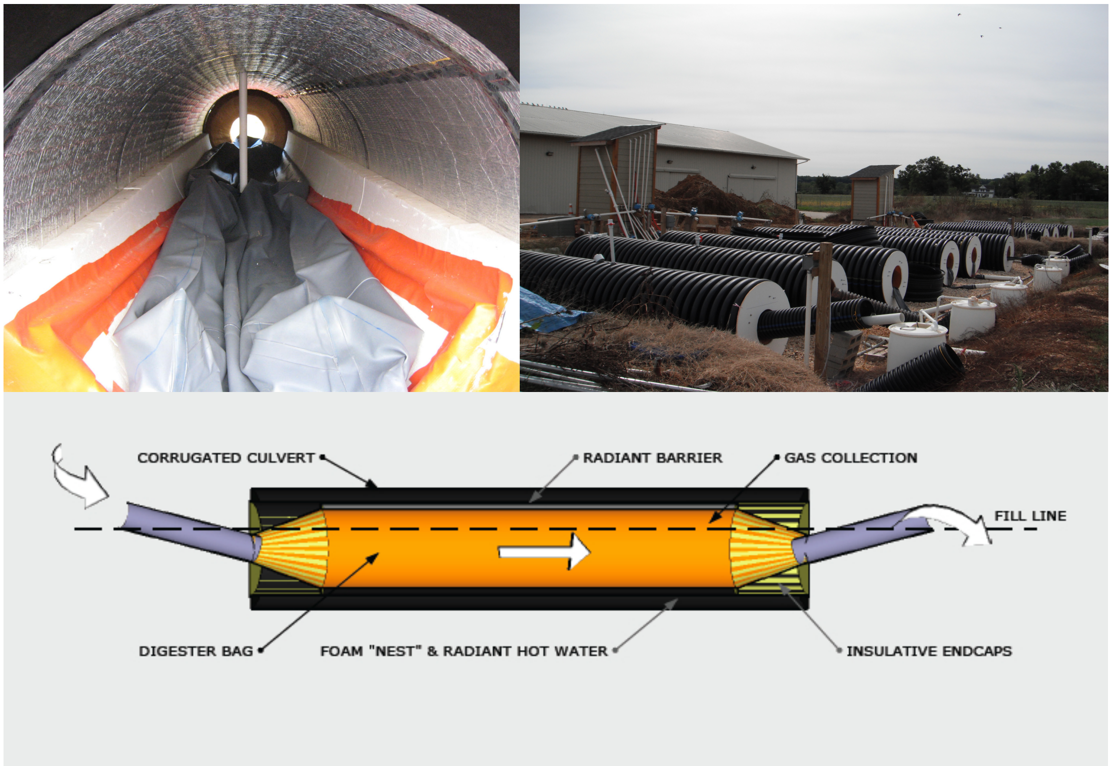


Figure 1-3 - The University of Maryland's modified plug-flow digesters. Upper left: The UMD design utilizes external radiant hot water heating (orange) to warm the digester, as well as a bed of foam insulation (white), a radiant barrier (silver), and foam end-caps to retain heat. Upper right: Digester site, showing digesters (black) and recirculation basins (white). Bottom: As with most plug-flow systems, manure enters the digester via gravity flow, displacing the digester contents and forcing digested manure out the back; a seal is maintained by the common level of manure at the fill line.

1.2.6.2 Modified Fixed-Dome Digesters

Fixed dome digesters may be the most ubiquitous digester design throughout the world, especially in southern Asia, where over thirty million digesters are currently operating (Burns, 2009). In tropical regions, most fixed-dome digesters are built from mortar and brick or plastic and are gravity fed a liquid waste substrate.

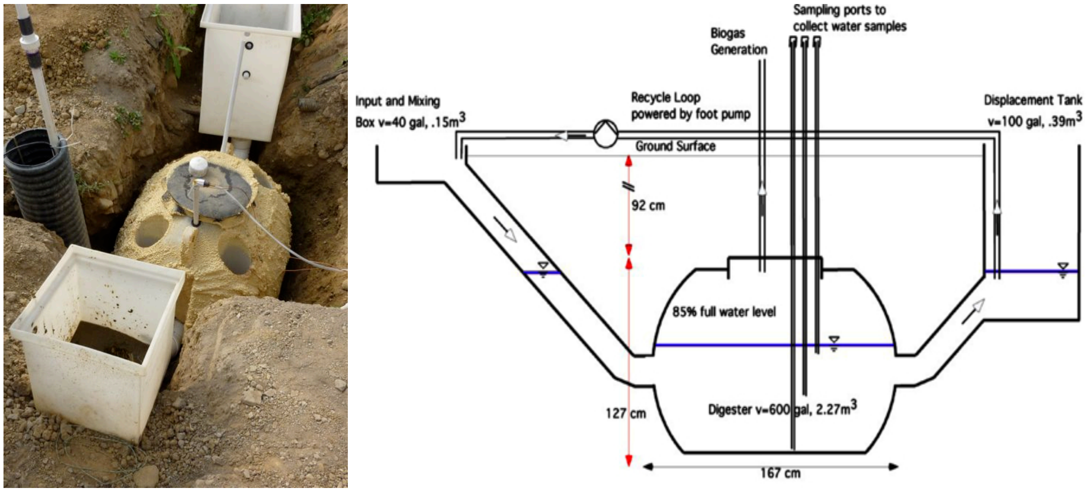


Figure 1-4 – The Ohio State modified fixed-dome digester. Left: Spray foam insulation prior to burial. Right: A schematic representing the digester's operation. Credit: Jay Martin, OSU

In the United States, fixed-dome digesters are currently being researched to explore their suitability for temperate climates. Ohio State University has designed a pilot-scale, insulated fixed-dome digester for the treatment of dairy manure, with a buried, spray-foam insulated, polyethylene storage tank retrofitted with influent and effluent plumbing (Keck, 2011) that receives manure consisting of up to 10% total solids. Gas pressure in the digestion chamber fluctuates with gas production and usage – each time gas is released, manure in the influent and effluent piping flows back towards the tank, providing some degree of mixing (Keck, 2011). In addition, a foot pump is used for recirculation, providing for a healthy, homogenous microbial population throughout the tank. The HRT for the manure is between 20 and 30 days (Keck, 2011).

1.3 Products of Anaerobic Digestion - Biogas

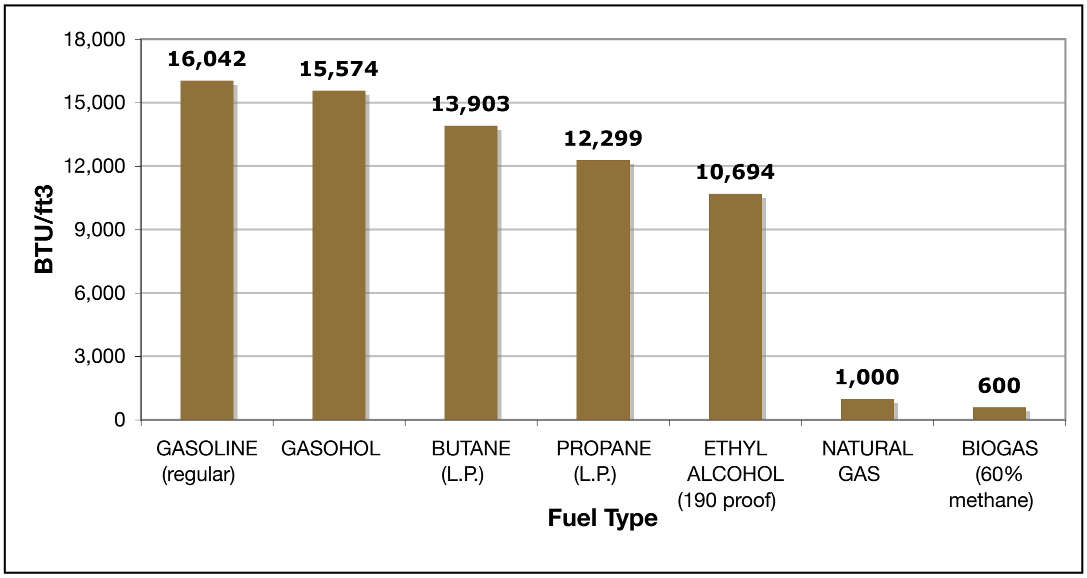


Figure 1-5 - Energy contents of standard fuels. As a guide, just over 1,000BTUs are required to heat one gallon of water from room temperature to boiling. Adapted from Barker (2001).

Biogas is the mixture of gases produced by the microbial communities within anaerobic digesters, and usually consists of 50-80% methane, 20-50% carbon dioxide, around 1% water vapor, and trace levels of other gases such as hydrogen sulfide, hydrogen, and ammonia. Because methane – the primary component of natural gas - is the main energy-containing constituent, the energy content of biogas is directly related to the amount of methane it contains (IEA, 2005; Schievano et al., 2011). The specific energy for biogas is often based on a theoretical methane content of 60%. In reality, the energy content of biogas will vary according to the proportion of methane it contains, but will never be greater than 1000BTU per cubic foot – the amount of energy contained in one cubic foot of pure methane. Depending on the digester feedstock, other gases may be generated in proportionally small amounts. These gases are generally harmless, but in some instances they may be problematic (for instance, hydrogen sulfide has been cited as a major contributor to anaerobic digestion system failures) (Lusk, 1998; Scott et al., 2010)).

1.3.1 Predicting Biogas Production

Tests measuring the concentration of organics in waste streams can be correlated to potential biogas production. The following methods are mentioned frequently in anaerobic digestion papers and discussions.

1.3.1.1 Chemical Oxygen Demand (COD)

Chemical oxygen demand (COD) testing relies on harsh chemicals to oxidize waste, providing an indicator of how much oxidizable, or energy-containing, material a waste sample contains (Boyles, 1997). Results are generally given on a weight per volume basis, and this information is used to forecast biogas production. Theoretically, 5.60 cubic feet of methane can be produced from every pound of COD destroyed in a waste sample (Osojnik, 2011), although actual production will depend on the amount of COD "converted" to biogas during digestion (Table 1-2).

1.3.1.2 Volatile Solids (VS)

Volatile Solids (VS) testing provides a proxy for the amount of biologically available carbon in organic wastes by measuring the amount of combustible matter present in a given sample. VS tests are conducted by establishing a dry weight for a waste sample – referred to as its total solids (TS) content – and then burning that sample at high temperatures (550ºC)(APHA, 2005). The amount of the sample that is burned off represents the volatile solids (VS) content and, by serving as an indicator for the organic matter content of the waste, it can provide insight into potential biogas production. Depending on the waste, 12.0 to 18.0 cubic feet of biogas are produced per pound of VS destroyed – or around 7.80 to 11.7 cubic feet of methane per pound VS destroyed (Metcalf and Eddy, Inc., 2003).

Table 1-2 - Average biogas production for various livestock from NRCS Technical Note No.1 (Beddoes et al., 2007).

Animal Type	Animal Units (1,000 lb)	COD (lb/AU/ day)	% Manure Collected	% COD Conversion	CH_4/lb COD (ft^3)	% CH_4	Biogas/animal/ day (ft^3)
Dairy	1.40	18.0	90	30	6.3	65	65.9
Beef	1.00	5.2	90	30	6.3	65	13.6
Swine	0.16	6.1	100	60	6.3	65	5.6
Poultry	0.00	13.7	100	70	6.3	65	0.3

1.3.1.3 Biochemical Methane Potential (BMP)

Biochemical Methane Potential (BMP) testing is another common method used to test the biogas and methane production capacity of a given waste. Samples of the waste stream are collected, mixed with liquid from an operating digester (termed inoculum), and mixed and heated under ideal conditions for up to thirty days, or until biogas production declines or ceases (Moody, 2010). The amount of biogas produced from this test, and the proportion of methane it contains, provides valuable information on the biogas production potential of the waste stream to be digested.

1.3.1.4 Limitations to Biogas Production Predictions

Although COD, VS, and BMP testing provides useful information, COD and VS tests are meant to quantify the amount of biodegradable materials potentially available to the microbes in an anaerobic digestion system, but do not provide information on the amount of waste that the microbes will actually consume. This information can be inferred based on established variations associated with different types of waste, or can be gathered with the help of BMP testing. BMP tests tend to overestimate the amount of biogas produced by an organic waste, although methane production potential is generally fairly accurate (Moody, 2010).

1.3.2 Common Biogas Uses

1.3.2.1 Heating and Steam

Heating and steam are one of the simplest uses of biogas. In the absence of any type of upgrading (i.e. removal of carbon dioxide), one cubic foot of biogas can provide enough energy to boil one-half gallon of water. Many farms harness this potential by diverting biogas to boilers, where the resulting hot water and steam are used for sanitary cleaning and heating in milking parlors, farm facilities, or even residences. In addition, biogas-heated water can be used to maintain the operating temperature in the anaerobic digester, keeping the microbial population warm and active (Kramer, 2009; Lusk, 1998; Scott et al., 2010). The use of traditional boilers or furnaces may require farmers to adapt these systems for use with biogas. Because biogas has a lower energy value than natural gas or propane, burner outlet sizes may need to be increased to accommodate biogas flows.

Additionally, biogas may be directly combusted to generate steam, which can be used in adsorption-based refrigeration systems or for electricity generation. The latter is most often used in connection with a combined heat and power (CHP) co-generation system, where exhaust heat is used to boil water to power a steam turbine.

It is important to keep in mind that many farm-related heating requirements may only be needed for part of the year, while biogas is produced year-round. For that reason, the use of biogas for heating alone should be carefully considered to ensure that it is the best use of the available resource.

1.3.2.2 Electricity Generation

In the United States, electricity generation is the most common use of biogas produced from farm-based anaerobic digesters (AgSTAR, 2010a). In order to generate electricity from biogas, a number of considerations must be made. First and foremost amongst them is cost. The NRCS surveyed thirty-eight dairy farms with an average herd size of 1,284 cows and found that, on average, electricity generation – including all machinery, biogas scrubbing, flares, on-farm wiring, and operation and maintenance – constituted about 36% of total capital costs for the digestion system (Beddoes et al., 2007). They also found that these costs did not necessarily drop with decreasing farm size or digester complexity. For instance, they found that installing electric generation systems on the least expensive digestion systems – covered lagoons – required more capital as a percentage of the total, indicating relatively fixed costs for generators and maintenance.

A second consideration is the projected value of the electricity that you will produce. Based on data derived from surveys of New York and Wisconsin farms, dairies averaging 1290 cows and operating solely on cow manure produced 3.12kWh of electricity per cow, per day; other reports place the figure between 2 and 5.5kWh (Kramer, 2009; Mehta, 2002; Nelson and Lamb, 2002; Scott et al., 2010). These numbers are dependent upon the type of the generator used, the energy content of the waste stream, and the efficiency of the anaerobic digester, amongst other factors, so the expected production varies with different systems. Production information, combined with local electric rates and farm usage, are determining factors in the decision of whether to generate electricity on-farm from the produced biogas.

Many farmers opt to purchase combined heat and power (CHP) systems to increase the efficiency of biogas use (Torresani, 2010). These systems are designed to generate electricity using biogas and capture the heated exhaust for further use in hot-water heating, digester heating, etc. The use of CHP co-generators can push the biogas-to-energy efficiency as high as 80% (Lusk, 1998; Wilkie, 2011).

1.3.2.3 Engine Fuel

The use of biogas as an engine fuel is probably most common in Northern Europe and Scandinavia, although some sectors in the United States are beginning to explore this option (Torresani, 2010). Using biogas for engine fuel is a cleaner, lower-maintenance alterative to gasoline and diesel, but the biogas cannot be used for this purpose without extensive scrubbing to remove carbon dioxide, hydrogen sulfide, water vapor, siloxanes and other impurities that would otherwise corrode the engine (Bruijstens et al., 2008; International Energy Agency, 2005; Torresani, 2010). In a Wisconsin trial creating biogas for vehicle use, biogas was scrubbed to 94-98% methane, 0.5 – 2% carbon dioxide, and undetectable levels of hydrogen sulfide and siloxanes; European standards for biogas fuel use are similar (Bruijstens et al., 2008; Torresani, 2010).

Additional equipment and infrastructure requirements for converting biogas to engine fuel on farms include gas conveyance lines, professional-grade gas scrubbers, monitoring ports for periodic gas sampling, and a compressor unit and pressure regulators for gas packaging. Depending on the purity of the product, a gas-odorizing unit may also be required (Electrigaz Technologies Inc., 2008).

1.3.2.4 Natural Gas

Large-scale anaerobic digestion facilities are increasingly considering the possibility of upgrading their biogas to natural gas pipeline standards for resale to the grid. Purity requirements vary depending on the utility but, in general, biogas is required to be scrubbed to standards equaling or surpassing those required for use as engine fuel – i.e. 95% methane with undetectable levels of impurities. Equipment requirements include gas conveyance lines, professional-grade gas scrubbers, monitoring ports for periodic gas sampling, a compressor unit and pressure regulators for injecting gas into the grid, a flow meter, flow computer, gas quality sensor or specific gravity meter, and an odorizing unit.

1.3.2.5 Lighting

Although rarely used in the United States and Europe, the direct use of biogas for lighting is a viable possibility, especially for small-scale biogas operations. Gas lamps can be retrofitted or specially purchased to run on biogas, and reports have indicated that

1m^3 of biogas can provide 40-60W equivalent light for up to six hours (Nema, 2005; Sagar, 2007).

1.3.3 Impurities and Scrubbing

1.3.3.1 Hydrogen Sulfide (H_2S)

During the anaerobic digestion process, sulfur present in the waste stream and in the microbial population can be converted into hydrogen sulfide gas (Bruijstens et al., 2008; Torresani, 2010), a poisonous and highly corrosive substance that can destroy metal components, especially boilers and engines. When H_2S is mixed with water vapor and/or combusted, it can form sulfuric acid, a corrosive chemical to metals. Corrosion of engines and boilers caused by excess hydrogen sulfide in biogas is one of the most commonly cited concern and failure of agricultural anaerobic digestion systems (Lusk, 1998; Scott et al., 2010). As a result, hydrogen sulfide scrubbing is generally recommended for all uses, and regular checks and maintenance of engines – including regular oil changes – should be anticipated (Ciolkosz et al., 2009).

There are a number of products that are regularly marketed and used to remove H_2S from biogas, and nearly all rely on one or more of the same basic components: iron oxides (e.g. iron filings), zinc oxides, bacteria, alkaline solids or liquids (e.g. hydrated lyme), silicate adsorbents, amine solutions, and water (Zicari, 2003). These systems vary in their cost and complexity, primarily due to the purity of biogas desired.

1.3.3.2 Carbon Dioxide (CO_2)

Carbon dioxide is the second largest constituent of biogas, but has no useful energetic value to farmers. When attempting to use biogas as a vehicle fuel or when upgrading the gas to sell to natural gas utilities, carbon dioxide must be thoroughly removed to provide a pure methane product. To do this, a number of materials can be used, including water, polyethylene glycol, and a variety of different membranes (International Energy Agency, 2005).

1.3.3.3 Water Vapor

Water can constitute between 0.8% and 1.6% of biogas by weight (Schievano et al., 2011), depending on its temperature, and creates the risk of corrosion and freeze damage in gas lines and machinery over time. A simple condensation trap, designed to collect water that has condensed in the relatively cool piping leading away from a digester, is often enough to eliminate any problematic issues.

1.3.3.4 Siloxanes

If considering co-digestion with municipal waste-activated sewage sludge, attention should be paid to the potential presence of silicon-containing compounds often present in the waste in the form of residues from detergents, personal hygiene products, cosmetics, etc. During the digestion process, these compounds can be converted into siloxane – a gaseous compound that is converted into abrasive silica crystals during combustion and proceeds to wear away, and eventually destroy, engines and machinery (Appels et al., 2008). Most processes used to remove siloxanes from biogas rely on activated carbon to adsorb the chemical (Appels et al., 2008).

In order to maximize the lifetime of the system and protect the economic investment, biogas should be scrubbed of these impurities before being diverted to an electric generator or combined heat and power system.

1.4 Separated Solids and Bedding

In most digestion systems, manure solids will need to be separated prior to digestion (to accommodate the specific digester design) or post-digestion (to minimize solids settling in lagoons). Solids separated prior to digestion may be composted to create animal bedding material or a soil amendment for crops. Most farms in the United States separate manure solids post-digestion. This material is very often used directly as bedding, especially in thermophilic digestion system (130ºF), where pathogen destruction is highest. It should be noted that there are reports of both increased (Scott et al., 2010) and decreased (Lusk, 1998) incidences of mastitis on dairy farms using separated solids for bedding, so the decision regarding the end-use of solids should be made after consulting other anaerobic digester owners.

1.5 Nutrients

There is a common misconception that nutrient quantities are reduced during the anaerobic digestion process, but for the most part they are not. Although some nutrients may be taken up by microbes, settle out with solids during the digestion process, or be coverted to gases that exit the digester in the form of biogas, eventually most nitrogen and phosphorous that enter an anaerobic digester also exit (Burke, 2001; Schievano et al., 2011).

Most farm operations separate solids from the waste stream leaving their digester, which provides farmers with an easily applied liquid fertilizer. This fertilizer differs from traditional land-applied manure in several ways. First, odor is drastically reduced, which many farmers cite as reason enough to install an anaerobic digester (Kramer, 2009; Lusk, 1998; Scott et al., 2010). Secondly, nitrogen, phosphorous, and potassium transition from organic to inorganic forms during digestion (Burke, 2001; Schievano et al., 2011). Of particular importance is nitrogen, which is converted in large quantities to ammonium, a readily plant-available compound. Ammonium is also highly volatile, however, which means that it can transition to ammonia gas and escape with ease, especially given warm temperatures, windy conditions, and high pH (Meisinger et al., 2001). Total nitrogen losses from field applied manure via ammonia volatilization are often as high as 70% (Stevens et al., 1997), so care should be taken to store and apply digester effluent in a manner that minimizes nitrogen loss.

1.6 The Benefits of Anaerobic Digestion

Due to their growing role in waste treatment and energy production, the benefits of anaerobic digesters are well documented. Coupled with their ability to serve as a renewable energy source is their capacity to reduce overall methane and carbon dioxide emissions to the environment, thereby mitigating the effects of waste decomposition on global warming (Clemens et al., 2006; Pronto and Gooch, 2010). Furthermore, in addition to the documented reduction in odors, pathogen counts are reduced during the anaerobic digestion process (Berg and Berman, 1980; Massé et al., 2011; Umetsu et al., 2009). Despite these virtues, the overall environmental benefit of anaerobic digestion is often implicitly assumed and has not been thoroughly investigated.

1.6.1 Environmental Sustainability

Several methods of environmental accounting exist that provide a index for the overall environmental sustainability of systems, the most prominent of which are life cycle assessments (LCAs) and eMergy analysis. LCAs compile all material and energetic inputs into a system, quantify them, and provide results that allow analysts to identify correlations between inputs and outputs. Emergy analyses similarly assess all inputs to a system, with the key difference being that these values are multiplied by established solar energy equivalents, providing a common denominator for quantification and comparison of all inputs and outputs of the system.

Only a small number of LCAs and emergy analyses have explored anaerobic digestion. Bastianoni and Marchettini (2000) studied a dairy farm system utilizing anaerobic digestion for electricity production in Puerto Rico. They found the co-production of milk, methane, and electricity had a lower environmental impact and was more efficient than processes that focused operations on the creation of just one product. Björklund et al. (2001) examined electricity generation from biogas at wastewater treatment plants in Sweden and found anaerobic digestion for energy to be more resource intensive than conventional electricity production. Wei et al. (2009) used emergy analysis to investigate a greenhouse-based, integrated-agriculture “four-in-one peach production system” (FIOPPS) in China operating with an $8m^3$, buried anaerobic digester used for coordinated swine waste treatment and greenhouse heat production. They found the system to be more environmentally sustainable than other contemporary Chinese greenhouse operations. Zhou et al. (2010) studied a UASB (upflow anaerobic sludge bed) anaerobic digestion system designed for agricultural waste treatment of poultry and swine manure, which consisted of two digesters with operating capacities of $200m^3$ and $500m^3$, respectively. The products of anaerobic digestion included biogas, a nutrient-rich slurry, and recalcitrant solids used for soil amendments, and the emergy analysis found the system was more environmentally sustainable than traditional Chinese agricultural operations.

An emergy analysis of a Costa Rican digester system, consisting of two Taiwanese-model, plug-flow bag digesters (Ciotola et al., 2011), compared their emergy indices to that of Bastianoni and Marchettini (2000), Wei et al. (2009) and Zhou et al. (2009). The Costa Rican digesters treated dairy cow and swine manure, had a total operating capacity of $146m^3$, and produced a nutrient slurry and biogas, the latter of which was used to produce electricity. Similar to previous findings, they found that the system demonstrated a high level of environmental sustainability and that anaerobic digestion represented a viable agricultural practice for Costa Rican farms. In a study with similar objectives, Börjesson and Berglund (2007) conducted a life-cycle analysis (LCA) of biogas production systems in Sweden that found similar but widely varying increases in sustainability upon the implementation of AD systems in waste management scenarios. In all of the aforementioned emergy and LCA studies, the largest factor influencing sustainability was the origin and type of the feedstock being utilized.

1.7 Objectives of Research

This research was conducted to explore the environmental contributions of anaerobic digestion from two perspectives. In the study presented in Chapter 2, an eMergy analysis on a Haitian and U.S. waste generation and anaerobic digestion system was used to assess the effect of waste source, climate, and infrastructure on system sustainability. In the study presented in Chapter 3, a digestion trial on various was conducted to serve as a proxy for the waste treatment and energy production options for agricultural digesters treating dairy manure in the United States.

2 A COMPARATIVE EMERGY ANALYSIS OF TWO SMALL-SCALE ANAEROBIC DIGESTION SYSTEMS TREATING WASTE IN THE UNITED STATES AND HAITI

2.1 Introduction

The use of anaerobic digestion for the treatment and stabilization of organic wastes, the production of renewable energy, the reduction of greenhouse gas emissions and the creation of liquid fertilizers is well established as a viable means of waste treatment in many parts of the world (Clemens et al., 2006; Lusk et al., 1996; Mata-Alvarez et al., 2000; Müller, 2007). Anaerobic digestion is being increasingly promoted by businesses, development workers and policymakers (Bhaskar, 2010; Callahan, 2011; Murray, 2010), and the technology is proliferating both in the United States and abroad (Mi, 2007; AgSTAR, 2010b ; SNV Netherlands Development Organisation, 2011). However, the degree to which anaerobic digesters represent sustainable infrastructure appears to be implicitly assumed, and very few investigations have been conducted investigating the environmental impact of these systems. Furthermore, where one digestion system or design may succeed in the realm of environmental sustainability, another may fail – a fact that insinuates the need for a more comprehensive comparison of existing models as they relate to infrastructure, feedstock and the environments in which they operate.

Emergy analysis (emergy with an 'm') provides an effective vehicle for comparing varying systems. The use of emergy accounting as a tool for assessing total energy inputs into systems and economies is documented in scientific literature as a means of assessing environmental and monetary sustainability (Brown and Buranakarn, 2003; Campbell et al., 2005; Odum, 1996). Emergy is a portmanteau of the term 'embodied energy' and is based on accounting principles that valuate all naturally and anthropogenically-derived substances based on the cumulative solar energy used directly or indirectly to create them. Emergy analysis uses solar energy equivalents as common denominating units – termed solar emjoules (sej) – that allow for quantification and comparison of the energy inherent in both natural and socio-economic systems. Through the use of emergy analysis, the contributions of renewable and non-renewable components of labor, material, and feedstocks in anaerobic digestion can all be calculated and directly compared using indices that relate environmental sustainability. This information provides a platform upon which stakeholder decisions can be made that account for a system's sustainability. For the purposes of this report, environmental sustainability is defined as the ability to efficiently produce products over time with sustainable resource use and minimal environmental degradation, so that the ability of future generations to meet their needs is not compromised (UN-WCED, 1987).

Although several emergy studies have conducted analyses that relate information on varying aspects of specific digesters' sustainability, few exist comparing and contrasting anaerobic digesters (Bastianoni and Marchettini, 2000; Björklund et al., 2001; Ciotola et al., 2011; Wei et al., 2009; Zhou et al., 2010). Most previous emergy studies analyzing biogas production have examined agricultural wastes emanating from anaerobic digesters in the developing world, including Costa Rica, Puerto Rico, and China. All studies found that organic waste feedstocks were the most important contributor of embodied energy into anaerobic digestion systems. However, human waste, a frequently digested substrate in developing regions (Mshandete and Parawira, 2010), has not been investigated. In addition, only one study (Björklund et al., 2001) has examined digesters in Europe or the

United States, where at least 10,280 anaerobic digesters are operating on various agricultural and municipal feedstocks (AgSTAR, 2012; IEA, 2011; USEPA CHP Partnership, 2011). As feedstocks were deemed the most important contributing factor to overall emergy inputs and environmental sustainability, this study conducts separate emergy analyses for the creation of waste streams from feedstocks in order to investigate two anaerobic digesters in the construction phase of design – one treating human waste in Haiti, and the second operating on dairy waste in the United States – in order to gain a better understanding of how the type and origin of waste affects digestion systems.

2.1.1 Objectives and Scope

The specific objectives of this research are 1) to conduct an emergy analysis on two Taiwanese bag digestion systems and compare them to their counterparts in order to assess and highlight the effect of the waste source, climate and technological input on the system's environmental impact and sustainability; and 2) to use three new indices – the emergy yield equivalent (y_e), emergy efficiency index (EEI), and the adjusted yield ratio (AYR) – in combination with existing indices to compare the anaerobic digestion systems in order to provide more insight into the environmental effect of digesters treating various waste streams worldwide.

2.2 Methods

2.2.1 Site and Systems Descriptions

2.2.1.1 Haiti

The Haitian small-scale, plug-flow anaerobic digestion system is a pilot-scale system currently being constructed for a hospital complex operated by Zanmi Lasante, a

Partners in Health (PIH) facility on the Central Plateau of Haiti in the village of Cange (18º56’07” N, 71º59’31” W, elevation: 199 m). The climate is tropical, and average temperatures closely resemble those of the capital Port-Au-Prince, whose mean January and August temperatures are 27.1 ºC and 29.7 ºC, respectively (NOAA, 2011a).

The digesters are plug-flow, polyurethane bag digesters based on Taiwanese-bag digesters (Botero and Preston, 1987) designed to treat human waste generated by a portion of the PIH hospital. The system is comprised of three, 4 m^3 capacity bags, for a total operational capacity of 12 m^3 (~290 people/day) and an average hydraulic retention time of 15 days. The characteristics of the waste stream feedstock are variable, but averaged 1.5% total solids by volume, with an average volatile solids (VS) loading rate of 13.0 g/L and chemical oxygen demand (COD) loading rate of 41.0 g/L. Waste is conveyed to the digesters via a flushing latrine system (Appendix B: Haitian Latrine Designs).

2.2.1.2 USDA Beltsville Agricultural Research Center (BARC) Digesters

Figure 2-1 - Pilot-scale digesters developed by the University of Maryland

The University of Maryland plug-flow, pilot-scale AD system is located at the USDA Beltsville Agricultural Research Center (BARC) dairy facility in Beltsville, Maryland (39º1’47” N, 76º53’27” W, elevation: 34 m). The climate is temperate, with mean temperatures in January and July of 2.6 ºC and 25.6 ºC, respectively (NOAA, 2011). The BARC dairy herd consists of approximately 105 milking cows and 10 dry cows at any given time. Lactating cattle are housed, twenty-four hours per day and seven days per week, in a free-stall barn adjacent to the milking parlor. Dry cattle are sent to pasture and do not contribute to the manure treated by the Maryland anaerobic digesters.

Figure 2-2 – The Maryland PVC bag digester with insulation. Pictured is the 2" EPS foam "nest" (white), the PEX hot water piping (orange), the PVC biodigester bag (gray), the radiant barrier (silver material on ceiling of culvert), and the biogas port (white PVC pipe).

The University of Maryland digestion system consists of nine, 3.0 m^3 capacity, pilot-scale digesters, and was designed as a research tool to investigate the anaerobic digestion of agricultural livestock waste originating from small-scale (~100 cow) dairy farms. In an attempt to approximate the scale of the Haitian digestion system, the emergy calculations made in this study were based on a scaled-up version, 15.6 m^3 (~10 cow capacity) of the Maryland anaerobic digestion system with a 30-day hydraulic retention time (HRT). All materials and proportions of the existing digesters were maintained, and their availability in the market confirmed. The only exception was the materials and services associated primarily with research operations, which were omitted from the scope of the analysis.

Similar to its Haitian counterpart, the UMD digester design is adapted from the Taiwanese-bag digesters described by Botero and Preston (1987) and frequently installed in Latin America (Eaton, 2011; Lansing et al., 2010; Vízquez Arias, n.d.). The digesters consist of a polyvinyl chloride (PVC) geomembrane bag insulated by an expanded-polystyrene (EPS) "nest" and a closed-cell-foam-backed radiant barrier, heated via cross-linked polyethylene (PEX) hot water pipes. These materials are all enclosed in a high-density polyethylene (HDPE) corrugated culvert. A portion of the biogas created during the digestion process is burned in a modified tempering kettle (a water bath surrounding a manure heating chamber) in order to heat manure entering the system and to maintain operating temperatures within the digester through heated water that is pumped underneath the digester bags.

The digesters are pump fed with unseparated dairy manure consisting of manure, urine, sawdust bedding, and misting water (the latter on a seasonal basis). In early September of 2011, the waste stream was 6% solids by mass, with an average VS loading rate of 53.2 mg/g and COD loading rate of 34.3 g/L.

2.2.2 Emergy Analysis

2.2.2.1 Fundamental Procedures

Emergy accounting is a thermodynamically-based framework that transforms all energetic, biological, and material inputs and derivatives of a system or process into common-unit equivalents – solar emjoules – through the use of solar transformities (energy) or specific emergies (mass). Solar transformities and specific emergies, in turn, are values assigned to each system input based on the cumulative solar energy used directly or indirectly in the formation of one unit of the resource of interest (Odum, 1996). This study followed an established methodology for conducting emergy analyses (Odum, 1996), in which: 1) a system diagram is drawn to insure all factors affecting the system are accounted (Figure 2-3 through Figure 2-6); 2) all resource flows in and out of the system are quantified; and 3) all quantities are multiplied by either calculated or peer-reviewed solar transformity values to obtain a total emergy value (Table 2-3 to Table 2-6).

2.2.2.2 Additional Procedures Used in This Report

In order to arrive at an acceptable solar transformity for the waste streams entering each of the respective anaerobic digestion systems, standalone emergy analyses of each of the waste generation processes were conducted using the standard methodology (Odum, 1996). Specific emergy values (sej/g) were calculated or collected for the diets and infrastructure contributing to each system's respective waste stream.

To calculate Haiti's food consumption, all foods representing 0.1% or more of the caloric inputs to the average Haitian diet as reported by the United Nations' Food and Agriculture Organization (2012) were catalogued. The caloric content per gram of food input was multiplied by the solar transformity value from the literature to arrive at a specific emergy for each input. In the Maryland dairy feed system, all inputs to the prepared diet were catalogued and prescribed a specific emergy value from the literature.

For each input in both systems, the percentage of renewable emergy (ΦR) was determined either by 1) using the renewable component reported by previous studies; 2) calculating the proportional contribution of the largest solar-influenced biogeochemical process (usually evapotranspiration) to the overall emergy inputs, thereby avoiding double counting; or 3) multiplying the food's proportional content of emergy from labor by a standard renewable component for labor derived from Brandt-Williams (2002) and Castellini et al. (2006). These values were then combined with the known per capita consumption of the waste-generating system, and multiplied by the system population to arrive at an emergy value representative of the feedstock characteristics for each system. Additional emergy inputs from water, labor, and energy sources were allocated to each system based on reported values, and an overall emergy value was derived based on calculated quantities of waste generation.

Due to a lack of available data, no transportation, energy, or labor inputs were included for the construction of the Maryland dairy barn or the Haitian flushing latrine. In all four analyses conducted by this study, all one-time inputs were quantified and divided by the expected lifespans of the anaerobic digestion systems, dairy and latrine infrastructure, or assorted machinery to arrive at annualized emergetic contributions.

2.2.2.3 Analytical Measures

Biochemical Methane Potential (BMP) were conducted to determine the quantity of methane expected from human and dairy waste water entering the digesters, as the digesters used in this study were under construction at the point of this analysis. BMP trials are controlled tests used to assess the methane production potential of a given organic waste. This study followed protocols provided by Moody (2010) to project annual biogas production from each digestion system. Biogas was analyzed for methane content via FID gas chromatography (Agilent 5900 GC) with an injection temperature of

200 °C, a detector temperature of 250 °C, and helium used as the carrier gas at a flow rate of 300 ml/min.

Nutrient levels present in the digested slurry were measured differently for each digestion system. In the Haitian digester, the quantity of total nitrogen (TN) and phosphorus (TP) in the effluent was calculated based on literature data from which Jönsson et al. (2004) and Polprasert (2007) who state that 1.1% of protein consumed in a human diet can be measured as total phosphorus in human waste, and who provide research establishing levels of total nitrogen at 0.06 g N/g dry feces and 0.17 g N/g dry urine. In the Maryland system, TN was assessed using an elemental analyzer (Elementar Vario Max CNS), and TP was analyzed using an acid digestion procedure detailed in the Recommended Methods of Manure Analysis (Peters et al., 2003). Quantities of bedding for the Maryland system were calculated based on measurements of residual solids in the effluent.

Table 2-1 - Itemized components of the average 1979 kCal Haitian Diet

Rank	Product	Daily Caloric Value/Person (kCal)	% by kCal of Total	J/g[a]	Solar Transformity (sej/J)	Specific Emergy (sej/g)	Solar Emergy (sej)	% Renewable Emergy	Source	% of Total Emergy	Notes
1	Rice (Milled Equivalent)	406	20.5%	858	8.30E+04	1.28E+09	1.41E+11	7.2%	b, 1	3.16%	White rice, raw (China)
2	Wheat	238	12.0%	503	6.80E+04	9.16E+08	6.77E+10	7.2%	b, 2	1.52%	Whole grain, soft wheat flour (China)
3	Maize	222	11.2%	469	9.98E+04	1.52E+09	9.27E+10	31.0%	c, 3	2.08%	Calorie count from whole grain corn flour
4	Sugar (Raw Equivalent)	201	10.2%	425	2.10E+04	3.34E+08	1.77E+10	20.3%	d, 4	0.396%	Calorie count from brown sugar; transformity from cane sugar
5	Soybean Oil	100	5.1%	211	3.40E+05	1.35E+10	1.42E+11	23.4%	e, 1	3.19%	Transformity from Brazil
6	Alcoholic Beverages	74	3.7%	156	1.10E+05	1.33E+08	3.41E+10	20.5%	f, 2	0.764%	Light beer; transformity from ethanol
7	Beans	73	3.7%	154	2.93E+05	4.25E+09	8.95E+10	35.0%	c, 3	2.01%	Calorie count from pinto beans; transformity from Kenya
8	Cassava	71	3.6%	150	2.07E+04	1.39E+08	6.15E+09	38.0%	c, 3	0.138%	Transformity from Kenyan study
9	Palm Oil	64	3.2%	135	2.39E+04	8.84E+08	6.40E+09	25.2%	g, 1	0.144%	Transformity from Brazil
10	Sweet Potatoes	56	2.8%	118	3.83E+04	1.38E+08	8.97E+09	32.0%	c, 3	0.201%	Transformity from Kenyan study
11	Yams	48	2.4%	101	3.83E+04	1.89E+08	7.69E+09	32.0%	c, 3	0.173%	Tranformity of sweet potatoes
12	Milk	41	2.1%	87	8.66E+06	2.32E+10	1.49E+12	40.0%	c, 3	33.34%	3.7% milkfat; highland livestock (Kenya)
13	Bananas	38	1.9%	80	2.20E+05	8.19E+08	3.50E+10	3.7%	h, 1	0.785%	Transformity from Chinese study
14	Sorghum	36	1.8%	76	2.10E+05	2.98E+09	3.16E+10	32.0%	c, 3	0.710%	Transformity from Kenyan study
15	Pig meat	33	1.7%	70	6.72E+06	3.37E+10	9.28E+11	13.9%	c, 4	20.8%	Combined lean and fat
16	Plantains	31	1.6%	66	3.17E+04	1.62E+08	4.11E+09	52.0%	c, 3	0.0923%	Cooking bananas (Kenya)
17	Pulses (chickpeas, dry peas, & lentils)	26	1.3%	55	1.60E+05	4.76E+08	1.74E+10	13.9%	c, 4	0.391%	Transformity from Kenyan study
18	Assorted fruits	26	1.3%	55	1.32E+06	2.62E+09	1.44E+11	2.4%	h, 1	3.22%	Guava and papaya
19	Assorted oils	25	1.3%	53	2.02E+05	7.47E+09	2.11E+10	22.2%	e, g, i, 1, 5	0.474%	Average of soybean, palm, and olive oils
20	Bovine meat	25	1.3%	53	8.60E+05	4.85E+10	9.00E+10	33.4%	d, 4	2.02%	Transformity of beef (Florida)
21	Groundnuts	21	1.1%	44	1.21E+05	2.87E+09	1.06E+10	31.0%	c, 3	0.239%	Transformity from Kenyan study
22	Poultry	15	0.8%	32	5.79E+05	4.12E+09	3.63E+10	28.8%	j, 6	0.815%	Transformity of chicken with skin (Italy)
23	Assorted vegetables	14	0.7%	30	7.04E+05	1.51E+10	4.12E+10	8.7%	d, 4	0.925%	Average of cucumber, green beans, and lettuce (Florida)
24	Assorted roots	12	0.6%	25	1.98E+04	8.12E+07	9.94E+08	35.3%	c, 3	0.0223%	Average of potatoes, sweet potatoes, and cassava (Kenya)
25	Raw sugar	11	0.6%	23	2.10E+04	3.34E+08	9.67E+08	20.3%	d, 4	0.0217%	Brown sugar
26	Coconuts	10	0.5%	21	4.81E+03	7.12E+07	2.01E+08	8.3%	k	0.00451%	Raw coconut meat
27	Raw animal fats	8	0.4%	17	3.79E+06	1.42E+11	1.27E+11	23.7%	c, d, 4	2.85%	Caloric content from bacon grease; transformity is average of beef and pork
28	Assorted cereals	6	0.3%	13	1.13E+05	1.79E+09	2.84E+09	30.0%	c, 3	0.0637%	Transformity from millet
29	Coffee	6	0.3%	13	1.74E+05	1.75E+09	4.37E+09	40.0%	c, 3	0.0980%	Transformity from Kenyan study
30	Sesame seed	5	0.3%	11	--	--	--	--	--	--	

31	Oranges, mandarines	4	0.2%	2092	1.09E+05	2.28E+08	1.82E+09	17.8%	d, 4	0.0409%	Transformity from Florida study
32	Mutton & goat meat	4	0.2%	4561	2.86E+06	1.30E+10	4.79E+10	13.9%	As cited in (c), 4	1.074%	
33	Assorted meats	4	0.2%	6569	3.22E+07	2.12E+11	5.39E+11	29.1%	c, d, 3, 4	12.1%	Average of pig, bovine, and Kenyan highland meats
34	Pelagic fish	4	0.2%	6945	8.47E+06	5.88E+10	1.42E+11	7.4%	As cited in (c), 4	3.18%	Caloric content from bluefish & sardines
35	Potatoes	3	0.2%	3222	1.78E+05	5.73E+08	2.23E+09	9.5%	d, 4	0.0501%	Transformity from Florida study
36	Peas	3	0.2%	3389	1.20E+06	4.07E+09	1.51E+10	10.6%	d, 4	0.338%	Transformity for green beans (Florida)
37	Tomatoes	2	0.1%	753	8.57E+05	6.45E+08	7.17E+09	3.7%	d, 4	0.161%	Transformity from Florida study
38	Freshwater fish	2	0.1%	4017	8.47E+06	3.40E+10	7.09E+10	7.4%	As cited in (c), 4	1.59%	Calorie count from tilapia
39	Sunflowerseed oil	1	0.1%	36987	--	--	--	--	--	--	
40	Onions	1	0.1%	1674	--	--	--	--	--	--	
41	Lemons, limes	1	0.1%	1255	1.09E+05	1.37E+08	4.56E+08	17.8%	d, 4	0.01023%	Transformity for oranges (Florida)
42	Cocoa beans	1	0.1%	16652	--	--	--	--	--	--	Powder
43	Marine fish	1	0.1%	5523	8.47E+06	4.68E+10	3.54E+10	7.4%	c, 4	0.795%	Processed grouper, mackeral, snapper
Total for Haitian Diet		**1973**	**99.7%**							100%	
Total Accounted		**1965**	**99.3%**								
EMERGY VALUES FOR HAITIAN DIET (PER PERSON)*					**5.38E+05**	**4.08E+09**	**4.46E+12**	**25.6%**		**This study**	

a) USDA Nutrient Data Lab, 2012; b) Xi and Qin, 2009; c) Cohen et al., 2006; d) Brandt-Williams, 2001; e) Derived from Cavalett & Ortega (2010); f) Felix & Tilley, 2009; g) Takahashi & Ortega, 2010; h) Lu et al., 2009; i) Khalaf et al., 2003; j) Castellini et al., 2006; k) Huong, 2005

1) Renewable component derived from rain; 2) Renewable component of a general human diet (15.4%, derived from evapotranpirative contributions to food production from Brandt-Williams (2002) & Castellini et al. (2006)) multiplied by human labor component of feedstock; 3) Renewable component from Cohen et al. (2006); 4) Renewable component derived from contributions of evapotranspiration; 5) Renewable component derived from Khalaf et al. (2003); 6) Renewable component from Castellini et al., 2006

* Solar transformity for diet calculated as $\frac{sej}{J} = \sum_{rank=1}^{n} sej/J_{rank} * \%\, kCal\ of\ total_{rank}$

* Specific emergy for diet calculated as $\frac{sej}{g} = \sum_{rank=1}^{n} sej/g_{rank} * \%\, kCal\ of\ total_{rank}$

Table 2-2 - Itemized components of the Maryland dairy ration

Rank	Ingredient	Contents	As Fed per Cow (kg)	Proportion by weight	Specific Emergy (sej/g)	Solar Emergy (sej)	Proportion Renewable Emergy	Source	% of Total Emergy	Notes
1	Corn sil BT	Corn sileage	16.6	39.8%	1.45E+10	2.41E+14	11.8%	a, 1	50.9%	Specific emergy of corn grain
2	DC Conc	Ground corn grain	7.78	18.6%	1.45E+10	1.13E+14	11.8%	a, 1	23.8%	
2a		Roasted whole soybean	1.52	3.62%	9.87E+09	1.50E+13	39.7%	a, 1	3.16%	Specific emergy of unprocessed soybeans
2b		Soybean meal	1.52	3.62%	1.82E+09	2.76E+12	29.7%	b, 2	0.582%	
2c		Soybean hulls	1.29	3.08%	9.87E+09	1.27E+13	39.7%	a, 1	2.68%	Specific emergy of unprocessed soybeans
2d		SoyPlus (soybean meal)	0.503	1.20%	1.82E+09	9.16E+11	29.7%	b, 2	0.193%	
2e		Pro-Lak (protein supplement)	0.503	1.20%	4.59E+09	2.31E+12	0.00%	c	0.488%	Specific emergy of protein mix
2f		Limestone	0.322	0.770%	1.68E+09	5.41E+11	0.00%	d	0.114%	
2g		Sodium bicarb	0.150	0.358%	1.00E+09	1.50E+11	0.00%	c	0.0316%	Taken from $Ca(HCO_3)_2$
2h		Salt-white	0.127	0.304%	6.52E+08	8.28E+10	0.00%	b	0.0175%	
2i		Dynamate (Mg & K_2SO_4)	0.0499	0.119%	6.14E+09	3.06E+11	0.00%	e	0.0647%	Specific emergy of Mg
2j		Mg oxide	0.0318	0.0759%	5.00E+08	1.59E+10	0.00%	f	0.00335%	
2k		VTM Premix 080101 (nutrient mix)	0.0249	0.0597%	4.14E+09	1.03E+11	0.00%	f	0.0218%	Specific emergy of minerals in feed
2l		Mepron M85 (methionine)	0.0181	0.0434%	4.59E+09	8.33E+10	0.00%	c	0.0176%	
2m		Vit E 20,000	0.0095	0.0228%	4.14E+09	3.94E+10	0.00%	f	0.00833%	Specific emergy of minerals in feed
2n		Availa 4 (micronutrient mix)	0.00408	0.0098%	4.14E+09	1.69E+10	0.00%	f	0.00357%	Specific emergy of minerals in feed
2o		Rumensin 90 (monnesin)	0.00136	0.00325%	1.48E+10	2.01E+10	0.00%	b	0.00425%	
2p		Rovimix H-2 (biosin)	0.00136	0.00325%	4.59E+09	6.25E+09	0.00%	c	0.00132%	
3	Alf-TTC silage	Alfalfa sileage	6.80	16.3%	3.97E+08	2.70E+12	82.0%	b, 3	0.570%	Specific emergy of alfalfa hay
4	Cottonseed whole	Cottonseed	0.907	2.17%	2.98E+09	2.70E+12	0.0%	g, 4	0.571%	Specific emergy of seed forage
5	Citrus pulp dehy	Dehydrated citrus pulp	0.907	2.17%	1.92E+09	1.74E+12	17.8%	a, 1	0.368%	
6	Sugar blend US 071116	Sugar beet	0.907	2.17%	8.44E+10	7.66E+13	13.5%	a, f	16.2%	Evapotranspiration of cabbage
7	Alfa hay early blm	Alfalfa hay	0.605	1.45%	3.97E+08	2.40E+11	82.0%	b, 3	0.0507%	
8	Grass hay mid blm	Grass hay	0.605	1.45%	9.41E+08	5.69E+11	41.2%	a, 1	0.120%	
9	Wheat straw	Wheat straw	0.605	1.45%	2.89E+08	1.75E+11	42.0%	a, b	0.0369%	
Totals			**41.82**	**100.0%**						
EMERGY VALUES FOR BARC DAIRY DIET (PER COW)*					**1.13E+10**	**4.74E+14**	**14.2%**			**This Study**

a) Brandt-Williams, 2001; b) Castellini et al., 2006; c) corrected from Brandt-Williams & Fodelberg, 2004; d) Odum (1996) corrected by a factor of 1.68 (Odum et al., 2000); e)Cohen et al., 2007; f) Brandt-Williams & Fodelberg, 2004; g) Derived from Fahd et al. (2012) and USDA Nutrient Data Lab (2012)

1) Renewable component derived from contributions of evapotranspiration; 2) Renewable component from Takahashi & Ortega (2010); 3) Renewable component as cited in Castellini et al. (2006); 4) Renewable component from Fahd et al. (2012)

* Specific emergy for feed ration calculated as $\frac{sej}{g} = \sum_{rank=1}^{n} sej/g_{rank} + proportion\ by\ weight_{rank}$

2.2.2.4 Assigning Splits and Co-Products

The characterization and accounting of metabolic by-products can be conducted using two differing methods: 1) co-production, in which each product is assigned all the emergy amassed in the production process with the transformity calculated by dividing the total amassed emergy by the quantity of product, or 2) splitting, in which each product is assigned an emergy value proportional to its output quantity resulting in equal transformity values. There is not clear consensus on which method to use in emergy analyses (Bastianoni and Marchettini, 2000; Brown and Herendeen, 1996; Hau and Bakshi, 2004; Li et al., 2010; Vieira and Domingos, 2004). For the waste production analyses, the primary products of these processes (feces and urine) were classified as splits for two reasons: 1) they were not the desired products of the process that produced them, and 2) emergy accounting dictates that materials resulting from the same process must not be double-counted (Odum, 1998), so splitting facilitated the recombination of feces and urine in the anaerobic digestion processes. In the dairy production system, milk was considered a co-product since it was the desired product of the process.

The products of the anaerobic digestion processes (biogas, nutrient slurry, separated solids) were analyzed as co-products, following a precedent set by Ciotola et al. (2011) who calculated all transformities for the immediate products of anaerobic digestion as co-products. Ciotola et al. (2011) also compared data from Zhou et al. (2010) and Wei et al. (2009) to their results, in the process converting the yields from Zhou et al. (2010) and Wei et al. (2009) to co-product values in order to allow direct comparison. In order to facilitate comparisons to these results, this study also analyzed the yields of the Haiti and Maryland anaerobic digestion systems as co-products.

2.2.2.5 Utilization of Emergy Indices

Emergy indices are used to assess the emergetic efficiency and environmental sustainability of each system (Brown and Ulgiati, 1999). The indices are based on three categories of inputs: renewable inputs, such as sunlight, that are available from the local environment (R); purchased inputs, such as fabricated building materials, imported at a cost from outside the system (P); and non-renewable, local resources, such as soil, that are available within the system but have limited availability (N). The emergetic yield of the system (Y) is the sum of all inputs R, P, and N.

Using these core categorical values, emergy indices such as the emergy yield ratio (EYR), the environmental loading ratio (ELR), and the emergy sustainability index (ESI) are derived. The EYR, defined as EYR = I/P, provides an indication of a system's efficiency in converting non-renewable resources into products, with larger values indicating greater efficiency. The ELR, defined as ELR = (P+N)/R, is a proxy for the negative effect a system may have on the surrounding environment. The ESI, defined as ESI = EYR/ELR, indicates overall system sustainability by assessing its emergetic production relative to its burden on the surrounding environment. In addition, the proportion of renewable inputs to a system can be calculated by the following formula: $\Phi R = R/I$.

2.2.2.6 New Emergy Indices: Emergy Yield Equivalents (y_e), the Emergy Efficiency Index (EEI), and the Adjusted Yield Ratio (AYR)

Three emergy indices – the System Emergy Yield Equivalent (Sy_e), the Emergy Efficiency Index (EEI) and the Adjusted Yield Ratio (AYR) – were developed for this analysis in order to more provide more insight into the relative value of products produced by the anaerobic digestion systems. To calculate these indices, emergy yield equivalents (y_e) were developed by substituting the transformity values of anaerobic digestion products with the literature transformity values of analogous products that displayed the same properties and provided the same services as the digestion products. For example, the primary functional component of biogas is methane due to its chemical composition and energy content. Using emergy yield equivalents, the methane produced from anaerobic digestion is given an equivalent transformity to methane harvested as natural gas. The same method applies to all products of the anaerobic digestion process – nitrogen and phosphorous are given the solar transformities of their fertilizer equivalents, and water is given a transformity most closely resembling solar transformities for groundwater in the region it is generated. The substituted transformity values are then multiplied by the quantity of digestion product to produce a y_e value for each product (Tables 2-8 to 2-12):

$$product\ specific\ \ y_e = T_{equiv\ x} * Qty_x$$

where $T_{equiv\ x}$ is the equivalent (substituted) transformity for the product (x), and Qty_x is the quantity of the product (x). To arrive at a system emergy yield equivalent (Sy_e), all product specific yield equivalents are summed:

$$Sy_e = \sum_{i=1}^{n} y_{e_i}$$

The emergy efficiency index (EEI) is then calculated by dividing the system emergy yield equivalent by the total of emergy inputs into the system (I):

$$EEI = \frac{Sy_e}{I}$$

The EEI defines the efficiency of a system in producing products analogous to natural resources and gauges the benefit of a system producing multiple products by relating them to contemporary market resources (a variation of the "joint transformity" $\left[\frac{I}{\sum energy\ content\ of\ products}\right]$ developed by Bastianoni and Marchettini (2000) in a similar effort to more fully address co-production). The EEI provides insight into the overall efficiency of a system, or maximum empower, by creating a relationship between emergetic inputs and analogous emergy output values. Values above 1.0 denote a process capable of providing the co-products at an emergetic cost less than the cost associated with producing individual analogous products through conventional methods.

The "adjusted yield ratio" (AYR) was developed to accompany the EEI and is defined as the system yield equivalent divided by the system's purchased emergy inputs (P):

$$AYR = \frac{Sy_e}{P}$$

Whereas the environmental yield ratio (EYR) is defined as a "a measure of (each system's) net contribution to the economy beyond its own operation" (Odum, 1996), the AYR serves as an index of a system's efficiency in converting renewable and/or local resources into products comparable to those pre-existing in the market.

2.2.2.7 Sensitivity Analysis

Sensitivity analysis is often used in the emergy field as a means of gauging the effects of varying solar transformities and energy allocations of key inputs (Martin et al., 2006). In this report, a sensitivity analysis was conducted by doubling and halving the yearly emergy inputs of each material (Odum and Odum, 2000). Each emergy ratio was then recalculated to assess the resulting effect on the system's overall environmental sustainability. In keeping with Martin et al. (2006) and Ciotola et al. (2011), only inputs whose alterations that resulted in changes of greater than 10% to the overall emergy indices were noted.

2.3 Results

2.3.1 Food/Dairy Ration Analyses

2.3.1.1 Analysis of Haitian Human Diet

To calculate the food input of the Haiti waste generation system, a complete analysis of the Haitian diet was conducted (Table 2-1). Although constituting only 2.1% of the total caloric value of the Haitian diet, milk's high solar transformity (8.66E+06 sej/J) led it to be the largest contributor of emergy to the diet, equaling 1.49E+12 sej or 33.3% of total inputs. Similarly, pig meat consumption constituted just 1.7% of the diet, but, due to its large transformity (6.72E+06 sej/J), it was the second largest emergetic contributor to the Haitian diet (9.28E+11 sej or 20.8%). The next largest contributors to total emergy in the Haitian diet included assorted meats (5.39E+11 sej), assorted fruits (1.44E+11 sej), soybean oil (1.42E+11 sej), pelagic fish (1.42E+11 sej), and finally rice (1.41E+11 sej), which was the largest caloric contributor to the Haitian diet (20.5% of the total). The total emergy for the Haitian diet per person was 4.46E+12 sej/year, with 25.6% renewable emergy, a specific emergy of 5.47+09 sej/g, and a solar transformity of 5.38E+05 sej/J (Table 2-1).

2.3.1.2 Analysis of Maryland Dairy Ration

In the analysis of the Maryland dairy ration, corn silage, which constituted 39.8% of the feed by weight, was found to have a relatively high specific emergy (1.45E+10 sej/g) and to be the largest contributor of emergy, totaling 2.41E+14 sej (51.0% of inputs). Ground corn grain (18.6% of the diet with a specific emergy of 1.45E+10 sej/g) was the second largest contributor to emergy inputs, equaling 1.13E+13 sej, or 23.8% of the total. Other significant contributors to emergy included a custom sugar blend containing sugar beets (7.66E+13 sej), roasted whole soybean (1.50E+13 sej), and soybean hulls (1.27E+13 sej). The total emergy of the Maryland dairy ration per cow was 4.74E+14 sej with a 14.2% renewable component and a specific emergy of 1.13E+10 sej/g (Table 2-2).

2.3.2 Waste Generation Processes

2.3.2.1 The Haitian Waste Generation Process

The energy systems diagram in Figure 2-3 illustrates the flow of inputs within the Haitian waste generation system. Solar radiation contributes to the ambient temperature, while water, propane, food and labor are used for cooking. Once consumed, these inputs are metabolized, converted into wastes, and deposited in the latrine in the form of urine and feces. The waste generation system shown in Table 2-3 represents a population of 290 people using the latrine on a daily basis; it was assumed that each person produced 520 g of feces and 1 L of urine per day (Polprasert, 2007).

Renewable inputs to the Haitian waste generation totaled 1.88E+17 sej/year, or 23.7% of total emergy inputs, and included contributions from solar insolation, food, groundwater, labor and building materials, as shown in Table 2-3. Purchased inputs totaled 6.08E+17 sej/year (76.3% of inputs) and included (in descending order of transformity) propane for cooking, the non-renewable fraction of food and labor, and the non-renewable contributions of materials for the latrine, such as concrete, rebar and PVC piping.

The creation of human waste was found to require 7.96E+17 sej/year. The specific emergies for human feces and urine were calculated as splits and, by definition, had identical values of 4.36E+09 sej/g, with values derived from the proportional mass of each product produced (5.52E+07 and 1.27E+08 g/yr, respectively). The sensitivity analysis of the Haitian human waste generation process revealed that only renewable and purchased inputs of food and labor showed responses of greater than 10% of their original value when doubled or halved (Table 2-13). The EYR for the Haitian waste generation system was 1.31, the ELR was 3.23, and the ESI was 0.41 (Table 2-7).

2.3.2.2 The Maryland Waste Generation Process

Figure 2-4 depicts the energy flows within the Maryland waste generation system. Solar radiation and heating maintain comfortable temperatures for the dairy herd, while materials, energy, and labor are required to build the barn and milking parlor, and labor is required for maintenance. Additional labor and machinery are required to process the ration and feed it to the cows, which consume the feed and water in order to produce milk. Feces, urine, and some bedding – together referred to as manure – are scraped to a holding pit where it is later pumped to the anaerobic digestion system. Each milking cow is fed an average of 41.8 kg of feed/day, and around 654 kg/day of bedding are provided for the 105 cows contributing to overall manure production.

Renewable emergy contributions to the Maryland waste production process represented 2.66E+18 sej/year (13.1% of the total). Dairy feed was the largest contributor of renewable emergy (2.57E+18 sej/year, or 12.7%), while labor was the only other significant input (7.73E+16 sej/yr or 0.4%). Other inputs included solar insolation, bedding, and building materials. Purchased inputs contributed 1.76E+19 sej/year (86.9% of the total), and dairy feed was the largest purchased emergy input (1.56E+19 sej/year or 77.0% of the total). Other significant purchased inputs included labor (1.50E+06 sej/year), copper wiring (2.41E+17 sej/year), electricity (9.04E+16 sej/year), concrete (6.37E+16 sej/year), gravel (6.06E+16 sej/year), wood chip bedding (1.70E+16 sej/year), and diesel (1.25E+16 sej/year).

The Maryland waste generation system required 2.02E+19 sej/year for the production milk, feces, and urine. As in the Haitian analysis, the feces and urine that comprised the dairy manure were treated as splits to allow for clear accounting in the analysis of the anaerobic digestion system. As splits, dairy feces and urine each had a specific emergy of 9.60E+09 sej/g. Milk was treated as a co-product and had a specific emergy of 1.32E+10 sej/g. The sensitivity analysis for the Maryland dairy waste generation process showed significant responses only to the doubling and halving of renewable and purchased dairy feed (Table 2-13). The EYR for the Maryland waste production system was calculated as 1.15, the ELR value was 6.61, and the ESI was 0.17 (Table 2-7).

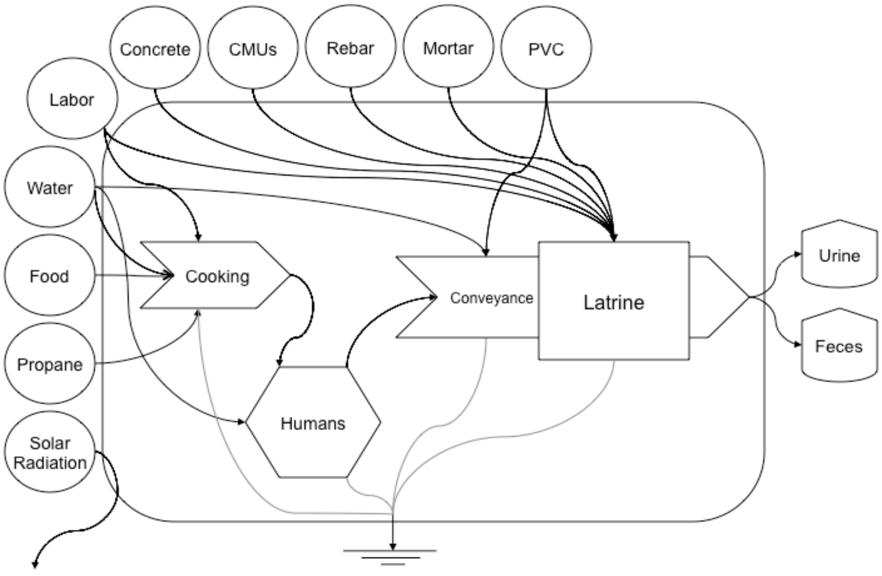


Figure 2-3 - Emergy system diagram of the Haitian food and waste generation process. Abbreviated materials are concrete masonry units (CMUs) and polyvinyl chloride (PVC).

Table 2-3 - Emergy table for the Haitian waste generation system

#	Item	Unit	Amount Per year	Solar Transformity (sej/unit)	Ref. for Transf.	Solar Emergy (sej/yr) E12	% Contribution to Total
Renewable Resources [R]							
R1	Solar Radiation	J	8.12E+11	1.00E+00	By definition	8.12E-01	0.0%
R2	Food	J	2.63E+11	5.38E+05	a	1.42E+05	17.8%
R3	Groundwater	g	3.18E+08	1.14E+06	b	3.62E+02	0.0%
R4	Labor	J	4.64E+09	1.00E+07	c	4.64E+04	5.8%
R5	Concrete	g	2.77E+04	6.93E+08	d	1.92E+01	0.0%
R6	CMUs	g	2.44E+04	7.58E+08	d	1.85E+01	0.0%
R7	Rebar	g	9.54E+03	2.77E+09	d	2.64E+01	0.0%
R8	Mortar	g	1.84E+03	3.31E+09	e	6.08E+00	0.0%
Total [R]						**1.88E+05**	**23.7%**
Purchased Resources [P]							
P1	Propane	g	1.37E+12	4.35E+04	f	5.96E+04	7.5%
P2	Food	J	7.65E+11	5.38E+05	a	4.11E+05	51.7%
P3	Labor	J	1.35E+10	1.00E+07	c	1.35E+05	16.9%
P4	Concrete	g	9.97E+05	6.93E+08	d	6.91E+02	0.1%
P5	CMUs	g	5.43E+05	7.58E+08	d	4.11E+02	0.1%
P6	Rebar	g	2.18E+05	2.77E+09	d	6.03E+02	0.1%
P7	Mortar	g	6.62E+04	3.31E+09	e	2.19E+02	0.0%
P8	PVC	g	8.43E+03	9.86E+09	e	8.31E+01	0.0%
Total [P]						**6.08E+05**	**76.3%**
Total Emergy Inputs [I]						**7.96E+05**	**100.0%**
Yield [Y]							
Y1	Feces	g	5.52E+07	4.36E+09	This report	2.41E+05	30.2%
Y2	Urine	g	1.27E+08	4.36E+09	This report	5.56E+05	69.8%

a) This study; b) Buenfil, 2001; b) Derived from Brandt-Williams, 2001; c) (Odum, 1996) corrected by a factor of 1.68 (Odum et al., 2000); d) Haukoos, 1995; e) Pulselli et al., 2007; f) Bastianoni et al., 2009

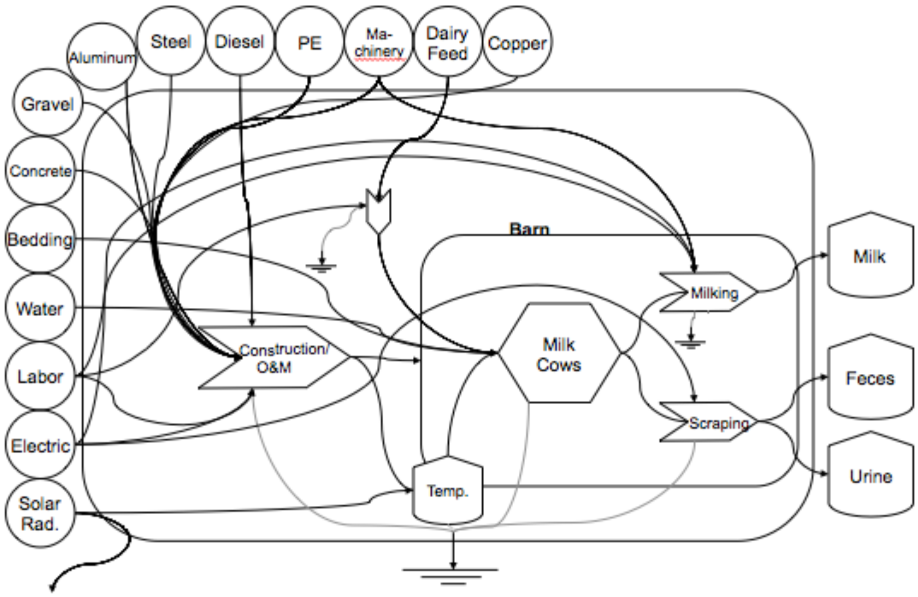


Figure 2-4 - Systems diagram of the Maryland dairy feed and waste generation process. Abbreviated material is polyethylene (PE).

Table 2-4 - Emergy table for the Maryland dairy waste generation process

Emergy Table for the Beltsville, MD, Dairy System

#	Item	Unit	Amount Per year	Solar Transformity (sej/unit)	Ref. for Transf.	Solar Emergy (sej/yr) E12	% Contribution to Total
Local Renewable Resources [R]							
R1	Solar radiation	J	2.38E+10	1.00E+00	By definition	2.38E-02	0.0%
R2	Labor	J	7.73E+09	1.00E+07	a	7.73E+04	0.4%
R3	Wood chip bedding	g	1.56E+07	3.17E+08	b	4.95E+03	0.0%
R4	Concrete	g	5.36E+05	1.20E+09	c	6.44E+02	0.0%
R5	Galvanized steel	g	2.09E+04	2.77E+09	c	5.79E+01	0.0%
R6	Dairy feed	g	2.27E+08	1.13E+10	This study	2.57E+06	12.7%
Total [R]						**2.66E+06**	**13.1%**
Purchased Resources [P]							
P1	Electricity	J	3.36E+11	2.69E+05	a	9.04E+04	0.4%
P2	Labor	J	1.50E+11	1.00E+07	a	1.50E+06	7.4%
P3	Potable water	L	4.69E+06	3.00E+08	d	1.41E+03	0.0%
P4	Wood chip bedding	g	5.37E+07	3.17E+08	b	1.70E+04	0.1%
P5	Concrete	g	5.31E+07	1.20E+09	c	6.37E+04	0.3%
P6	Gravel	g	4.67E+07	1.30E+09	e	6.06E+04	0.3%
P7	Aluminum	g	3.03E+01	1.81E+09	f	5.48E-02	0.0%
P8	Galvanized steel	g	1.88E+06	2.77E+09	c	5.21E+03	0.0%
P9	Diesel	g	4.41E+06	2.83E+09	g	1.25E+04	0.1%
P10	Polyethylene	g	3.60E+03	8.85E+09	h	3.19E+01	0.0%
P11	Farm machinery	g	6.95E+05	9.24E+09	i	6.42E+03	0.0%
P12	Dairy feed	g	1.37E+09	1.13E+10	This study	1.56E+07	77.0%
P13	Copper wiring	g	2.46E+06	9.80E+10	j	2.41E+05	1.2%
Total [P]						**1.76E+07**	**86.9%**
Total Emergy Inputs [I]						**2.02E+07**	**100.0%**
Yield [Y]							
Y1	Milk	g	1.53E+09	1.32E+10	This study	2.02E+07	100.0%
Y2	Feces	g	1.47E+09	9.59E+09	This study	1.41E+07	69.8%
Y3	Urine	g	6.38E+08	9.59E+09	This study	6.12E+06	30.2%

a) (Odum, 1996) multiplied by factor of 1.68 (Odum et al., 2000); b) Franzese et al., 2009; c) Haukoos, 1995; d) Buenfil, 2001; e) Campbell et al., 2005; f) Brown & Buranakarn, 2003; g) Bastianoni et al., 2009; h) Pulselli et al., 2007; i) derived from Pulselli et al., 2007; j) Cohen et al., 2007

2.3.3 Anaerobic Digestion Processes

2.3.3.1 Haitian Anaerobic Digestion Process

The systems diagram for the Haitian anaerobic digestion system (Figure 2-5) shows inputs from labor and materials to the construction, operation, and maintenance of the system, as well as groundwater inputs used in conveyance and solar insolation that provides heat to the digester environment. The digester processes the flow of 585 L/day of conveyance water carrying approximately 151 kg/day of human feces and 291 L/day of human urine.

Renewable resource inputs represented 1.89E+17 sej/year, or 23.6% of annual emergy inputs, in the Haitian anaerobic digestion system. These inputs included solar insolation as well as fractional components of feces, urine, and labor derived from this study's waste generation analysis. The total annual emergy inputs from the renewable component of human urine had the largest emergetic contribution (1.31E+17 sej/year), constituting 16.5% of total emergy input. Feces had the second highest renewable energy input (7.1%) with a total emergy value of 5.69E+16 sej/yr.

Purchased resources totaled 6.09E+17 sej/year (76.4% of inputs) and included the non-renewable fraction of the labor, feces, and urine, as well as all of the labor and materials used during construction of the anaerobic digestion system. Human urine contributed the largest amount of purchased emergy to the system (4.24E+17 sej/year, or 53.1% of the total), while human feces contributed the second largest quantity (1.84E+17 sej/year, or 23.0%). Labor and maintenance and PVC-based materials contributed

8.41E+14 sej/year and 4.91E+14 sej/year, respectively, or 0.1% each to total emergy inputs to the system.

The Haitian anaerobic digestion system required 7.98E+17 sej/year for the production of biogas, nutrients, and water. Biochemical methane production (BMP) tests found that the combined feces and urine added to the system produced approximately 9.15 L CH_4/L of waste introduced. This resulted in the production of 5.32E+10 J/year of methane, yielding a co-product solar transformity of 1.50E+07 sej/J for the biogas produced from the Haitian digestion system. Based on data provided by Jönsson et al. (2004) and Polprasert (2007), it was estimated that 1.30E+06 g/year nitrogen and 3.03E+05 g/year phosphorus were provided by the Haitian digester, resulting in specific emergies of 6.14E+11 sej/g and 2.63E+12 sej/g, respectively. An estimate of water production was based on the volume of water in the overall waste introduced to the digester minus approximately 0.7 L/day of water lost in the biogas. The resulting total was 3.65E+08 g/year of non-potable water with a specific emergy of 2.19E+09 sej/g. The sensitivity analysis for the Haitian anaerobic digestion system showed significant responses only to the doubling and halving of renewable and purchased human feces and urine inputs (Table 2-13). The EYR for the Haitian AD system was calculated as 1.31, the ELR value was 3.23, the ESI was 0.406, the Sy_e was 3.33E+16 sej/year, the EEI was 0.0417, and the AYR was 0.0546 (Table 2-7).

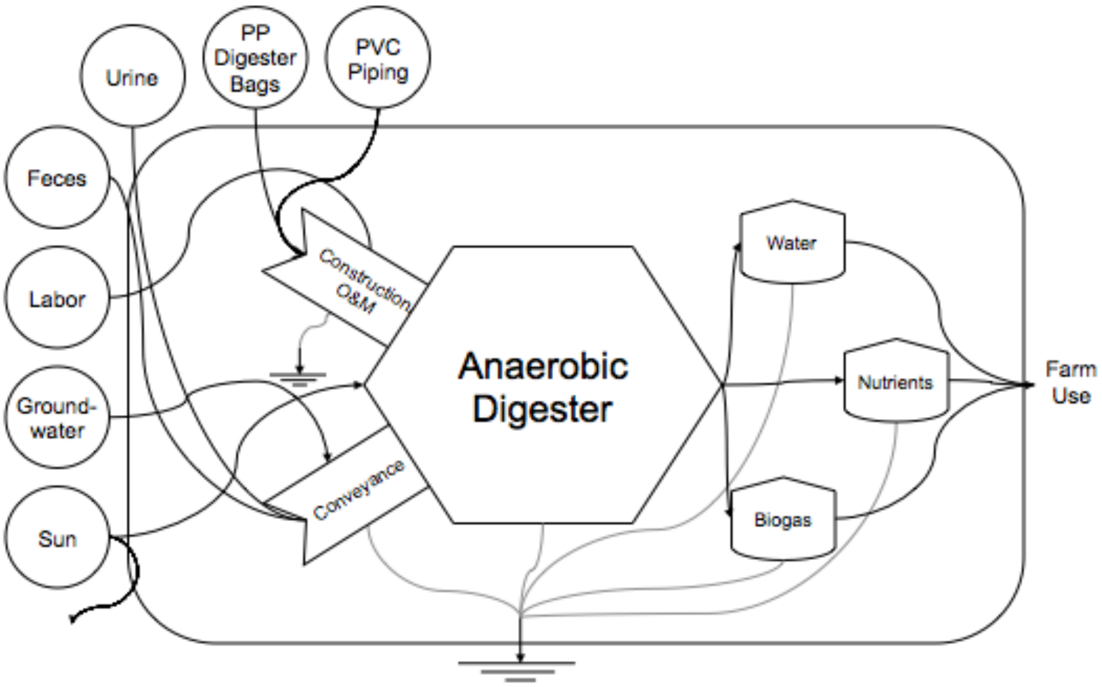


Figure 2-5 - Systems diagram for the Haitian digestion system. Abbreviated materials are polypropylene (PP) and polyvinyl chloride (PVC).

Table 2-5 - Emergy table for the Haitian digestion system

#	Item	Unit	Amount Per year	Solar Transformity (sej/unit)	Ref. for Transf.	Solar Emergy (sej/yr) E12	% Contribution to Total
Renewable Resources [R]							
R1	Solar Radiation	J	3.11E+08	1.00E+00	By definition	3.11E-04	0.0%
R2	Conveyance Water (Groundwater)	g	2.13E+08	1.14E+06	a	2.43E+02	0.0%
R3	Labor & Maintenance	J	1.53E+07	1.00E+07	b	1.53E+02	0.0%
R4	Human feces	g	1.30E+07	4.36E+09	e	5.69E+04	7.1%
R5	Human urine	g	3.01E+07	4.36E+09	e	1.31E+05	16.5%
Total [R]						**1.89E+05**	**23.6%**
Purchased Resources [P]							
P1	Labor & Maintenance	J	8.41E+07	1.00E+07	b	8.41E+02	0.1%
P2	Biodigester Bags (PP)	g	5.60E+03	9.86E+09	d	5.52E+01	0.0%
P3	Influent & Effluent Piping (PVC)	g	4.98E+04	9.86E+09	d	4.91E+02	0.1%
P4	Human feces	g	4.21E+07	4.36E+09	e	1.84E+05	23.0%
P5	Human urine	g	9.72E+07	4.36E+09	e	4.24E+05	53.1%
Total [P]						**6.09E+05**	**76.4%**
Total Emergy Inputs [I]						**7.98E+05**	**100.0%**
Yield [Y]							
Y1	Biogas	J	5.32E+10	1.50E+07	This report	7.98E+05	100.0%
Y2	Total Nitrogen	g	1.30E+06	6.14E+11	This report	7.98E+05	100.0%
Y3	Total Phosphorus	g	3.03E+05	2.63E+12	This report	7.98E+05	100.0%
Y4	Non-potable water	g	3.65E+08	2.19E+09	This report	7.98E+05	100.0%

a) Buenfil, 2001; b) Odum, 1996, corrected by a factor of 1.68 (Odum et al., 2000); c) Haukoos, 1995; d) Pulselli et al., 2007; e) This report; f) Bastianoni et al., 2009

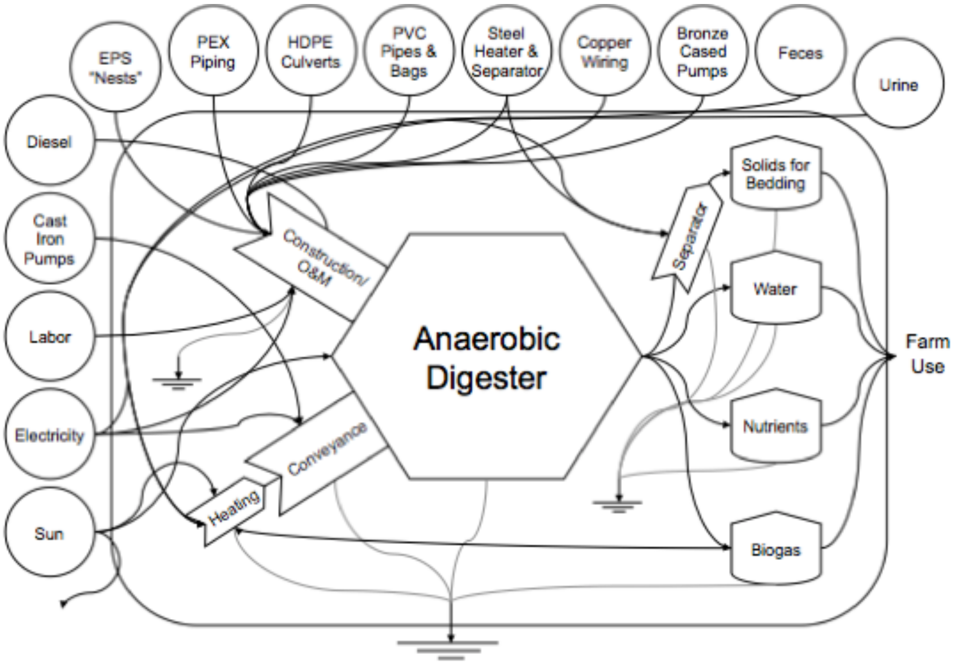


Figure 2-6 - Systems diagram for the Maryland digestion system. Abbreviated materials are expanded polystyrene (EPS), cross-linked polyethylene (PEX), high-density polyethylene (HDPE), and polyvinyl chloride (PVC).

Table 2-6 - Emergy table for the Maryland dairy anaerobic digestion system

#	Item	Unit	Amount Per year	Solar Transformity (sej/unit)	Ref. for Transf.	Solar Emergy (sej/yr) E12	% Contribution to Total
Local Renewable Resources [R]							
R1	Solar Radiation	J	3.21E+08	1.00E+00	By definition	3.21E-04	0.0%
R2	Labor & Maintenance	J	1.58E+07	1.00E+07	a	1.58E+02	0.0%
R3	Feces	g	1.73E+07	9.60E+09	b	1.66E+05	9.0%
R4	Urine	g	7.81E+06	9.60E+09	b	7.49E+04	4.1%
Total [R]						**2.41E+05**	**13.1%**
Purchased Resources [P]							
P1	Electricity	J	3.73E+09	5.64E+05	a	2.11E+03	0.1%
P2	Labor & Maintenance	J	3.07E+08	1.00E+07	a	3.07E+03	0.2%
P3	Cast iron cased pumps	g	5.42E+03	1.74E+09	c	9.44E+00	0.0%
P4	Diesel	g	9.45E+03	2.83E+09	d	2.67E+01	0.0%
P5	Insulative nests (EPS)	g	2.59E+03	8.85E+09	e	2.29E+01	0.0%
P6	Hot water piping (PEX)	g	7.91E+02	8.85E+09	e	7.00E+00	0.0%
P7	Culverts (HDPE)	g	4.10E+04	8.85E+09	e	3.63E+02	0.0%
P8	Feces	g	1.14E+08	9.60E+09	b	1.10E+06	59.6%
P9	Urine	g	5.16E+07	9.60E+09	b	4.96E+05	26.9%
P10	Piping (PVC)	g	4.87E+03	9.86E+09	e	4.80E+01	0.0%
P11	Digester Bags (PVC)	g	3.48E+03	9.86E+09	e	3.43E+01	0.0%
P12	Solids Separator	g	2.50E+04	2.85E+10	c, e	7.13E+02	0.0%
P13	Stainless steel heating kettle	g	2.07E+04	5.53E+10	e, f	1.14E+03	0.1%
P14	Copper wiring	g	8.98E+02	9.80E+10	f	8.80E+01	0.0%
P15	Bronze cased pumps	g	1.36E+02	2.94E+11	f	4.01E+01	0.0%
Total [P]						**1.60E+06**	**86.9%**
Total Emergy Inputs [I]						**1.84E+06**	**100.0%**
Yield [Y]							
	Biogas	J	6.74E+10	2.74E+07	This study	1.84E+06	
	Total Nitrogen	g	3.64E+05	5.06E+12	This study	1.84E+06	
	Total Phosphorous	g	4.84E+04	3.81E+13	This study	1.84E+06	
	Bedding	g	8.41E+06	2.19E+11	This study	1.84E+06	
	Non-potable water	g	1.80E+08	1.03E+10	This study	1.84E+06	

a) (Odum, 1996) corrected by factor of 1.68 (Odum et al., 2000); b) This study; c) Haukoos, 1995; d) Bastianoni et al., 2009; e) Pulselli et al., 2007; f) Cohen et al., 2007

2.3.3.2 Maryland Anaerobic Digestion Process

Figure 2-6 illustrates the energy flows within the Maryland anaerobic digestion system, in which labor and material inputs are used for construction, operation, and maintenance of the digester. Dairy manure is the digester feedstock, and solar insolation provides heating, with biogas used as an additional heat source for the digester. The digester treats 520 L/day of dairy manure, with manure and bedding composing approximately 70% of total inputs and urine constituting the remaining 30%.

Renewable resources contributed 2.41E+17 sej/year, or 13.1% of all emergy inputs to the Maryland digestion system. The renewable component of dairy cow feces contributed the greatest renewable fraction (1.66E+17 sej/year) to the Maryland digestion process (9.0% of the total), while the renewable fraction of urine constituted 7.49E+16 sej/year (4.1%). Renewable inputs from solar insolation and labor accounted for less than 0.1% of emergy applied to the system.

Purchased resources accounted for 1.60E+18 sej/year, or 86.9% of all emergy inputs to the system. Dairy cow feces was the largest contributor of purchased emergy (1.10E+18 sej/year, or 59.6% of total inputs), while urine provided 4.96E+17 sej/year (26.9%), labor and maintenance contributed 3.07E+15 sej/year (0.2%), electricity 2.11E+15 sej/year (0.1%), and stainless steel 1.14E+15 sej/year (0.1%). All other inputs contributed less than 0.1% of the total emergy used within the system.

The analysis showed that the Maryland digestion system required 1.84E+18 sej/year for the production of biogas, bedding, nutrients, and water, which were all counted as co-products. After subtracting biogas used throughout the year for heating the anaerobic digestion system (3.02E+10 J/year), the Maryland digester produced 6.74E+10

J/year of biogas, resulting in a solar transformity of 2.74E+07 sej/J. Total nitrogen in the digester effluent totaled 3.64E+05 g/year, while total phosphorus equaled 4.84E+04 g/year, resulting in specific emergy values of 5.06E+12 sej/g and 3.81E+13 sej/g, respectively. The residual solids recovered for bedding totaled 8.41E+06 g/year, yielding a specific emergy of 2.19E+11 sej/g, while1.80E+08 g/year of non-potable water (1.03E+10 sej/g) was also produced. The sensitivity analysis for the Maryland system showed significant responses only to the doubling and halving of renewable and purchased human feces and urine inputs (Table 2-13). The EYR for the Maryland digester was calculated as 1.15, the ELR value was 6.64, the ESI was 0.173, the Sy_e was 1.44E+16 sej/year, the EEI was 0.00781, and the AYR was 0.00899 (Table 2-7).

Table 2-7 - Comparison of emergy indices across studies

Indice	Calculation	Haitian Waste Generation Process	Maryland Dairy Waste Generation	Haitian 12m^3 Digester (This Study)	Maryland 15.6m^3 Digester (This Study)	Chinese 8m^3 Digester (Wei et al., 2009)	Chinese 700m^3 Digester (Zhou et al., 2010)	Costa Rican 146m^3 Digester (Ciotola et al., 2011)
Inputs (I) in sej/year	R+N+P	7.96E+17	2.02E+19	7.98E+17	1.84E+18	1.28E+16	1.48E+18	1.59E+16
Biogas production (J)	yield	n/a	n/a	5.32E+10	6.74E+10	6.28E+09	5.50E+12	2.99E+11
Solar transformity of biogas (sej/J)	I/yield	n/a	n/a	1.50E+07	2.73E+07	2.04E+06	2.69E+05	5.32E+04
Proportion renewable (ΦR)	R/I	23.7%	13.1%	23.6%	13.1%	78.0%	87.0%	66.0%
Emergy yield ratio (EYR)	I/P	1.31	1.15	1.31	1.15	1.61	7.52	2.93
Environmental loading ratio (ELR)	(P+N)/R	3.23	6.61	3.23	6.64	0.280	0.150	0.520
Emergy sustainability index (ESI)	EYR/ELR	0.406	0.174	0.406	0.173	5.75	50.1	5.63
System Yield Equivalent (Sy_e) (sej/yr)	∑ye	n/a	n/a	3.33E+16	1.44E+16	1.92E+16	2.63E+17	1.86E+16
Emergy Efficiency (EEI)	∑ye/I	n/a	n/a	0.04169	0.00782	1.50	0.178	1.05
Adjusted Yield Ratio (AYR)	∑ye/P	n/a	n/a	0.05460	0.00900	6.86	0.886	3.43

Table 2-8 - Summary of Yield Equivalents – Haitian Anaerobic Digestion System

Value	Actual Product	Quantity per year	Unit	Equivalent	sej/unit	Unit	Total emergy equivalent [ye] (sej/yr)	Source
ye1	Biogas	5.32E+10	J	Methane	4.79E+04	J	2.55E+15	Bargigli et al., 2004; Bastianoni et al., 2005
ye2	N	1.30E+06	g	N fertilizer	2.22E+10	g	2.89E+16	Odum, 1996; Brandt-Williams, 2001
ye3	P	3.03E+05	g	P_2O_5 fertilizer	4.79E+09	g	1.45E+15	Odum, 1996; Brandt-Williams, 2001
ye4	Water	3.65E+08	g	Groundwater	1.56E+08	g	5.69E+16	Buenfil, 2001
System Emergy Equivalent (Sy_e)							**8.97E+16**	

Table 2-9 - Summary of Yield Equivalents – Maryland Anaerobic Digestion System

Value	Actual Product	Quantity per year	Unit	Equivalent	sej/unit	Unit	Total emergy equivalent [ye] (sej/yr)	Source
ye1	Biogas	6.74E+10	J	Methane	4.79E+04	J	3.22E+15	Bargigli et al., 2004; Bastianoni et al., 2005
ye2	N	3.64E+05	g	N fertilizer	2.22E+10	g	8.08E+15	Odum, 1996; Brandt-Williams, 2001
ye3	P	4.84E+04	g	P_2O_5 fertilizer	4.79E+09	g	2.32E+14	Odum, 1996; Brandt-Williams, 2001
ye4	Bedding	8.41E+06	g	Wood chips	3.17E+08	g	2.67E+15	Franzese et al., 2009
ye5	Water	1.80E+08	g	Groundwater	1.14E+06	g	2.05E+14	Buenfil, 2001
System Emergy Equivalent (Sy_e)							**1.44E+16**	

Table 2-10 - Summary of Yield Equivalents – Wei et al., 2009

Value	Actual Product	Quantity per year	Unit	Equivalent	sej/unit	Unit	Total emergy equivalent [ye] (sej/yr)	Source
ye1	Peach	5.75E+09	J	same	5.30E+05	J	3.05E+15	Luo, 2003 (as cited in Wei et al., 2009)
ye2	Peach Branch	4.18E+10	J	same	4.40E+04	J	1.84E+15	Lan et al., 2002 (as cited in Wei et al., 2009)
ye3	Swine	8.25E+09	J	same	1.70E+06	J	1.40E+16	Lan et al., 2002 (as cited in Wei et al., 2009)
ye4	Biogas	6.28E+09	J	Methane	4.79E+04	J	3.00E+14	Bargigli et al., 2004; Bastianoni et al., 2005
System Emergy Equivalent (Sy_e)							**1.92E+16**	

Table 2-11 - Summary of Yield Equivalents – Zhou et al., 2010

Value	Actual Product	Quantity per year	Unit	Equivalent	sej/unit	Unit	Total emergy equivalent [ye] (sej/yr)	Source
ye1	Biogas	5.50E+12	J	Methane	4.79E+04	J	2.63E+17	Bargigli et al., 2004; Bastianoni et al., 2005
ye2	Biogas slurry	1.87E+05	J	same	5.77E+06	J	1.08E+12	Geber & Björklund, 2001 (as cited in Zhou et al., 2010)
ye3	Biogas residue	2.20E+04	J	same	2.70E+04	J	5.94E+08	Value for manure from Wei et al., 2009 (as cited in Zhou et al., 2010)
System Emergy Equivalent (Sy_e)							**2.63E+17**	

Table 2-12 - Summary of Yield Equivalents – Ciotola et al., 2011

Value	Actual Product	Quantity per year	Unit	Equivalent	sej/unit	Unit	Total emergy equivalent [ye] (sej/yr)	Source
ye1	Biogas	2.99E+11	J	Methane	4.79E+04	J	1.43E+16	Bargigli et al., 2004; Bastianoni et al., 2005
ye2	N	1.87E+05	g	N fertilizer	2.22E+10	g	4.15E+15	Odum, 1996; Brandt-Williams, 2001
ye3	P	2.20E+04	g	P_2O_5 fertilizer	4.79E+09	g	1.05E+14	Odum, 1996; Brandt-Williams, 2001
System Emergy Equivalent (Sy_e)							**1.86E+16**	

Table 2-13 - Sensitivity analysis results for the Haitian and Maryland systems

Input values were doubled and halved to assess their effect on the ΦR, EYR, ELR, ESI, EEI, and AYR, and only changes of 10% or greater are listed. Dashes indicate changes of less than 10%.

		Haitian Human Waste System					**Haitian AD System**				
Emergy Indice	**Emergy Transformation**	**Original Values**	Renewable food	Renewable Labor	Purchased food	Purchased Labor	**Original Values**	Renewable Human Feces	Renewable Human Urine	Purchased Human Feces	Purchased Human Urine
Proportion renewable (ΦR)	Doubled	23.7%	35.2%	27.9%	15.6%	20.2%	23.6%	28.7%	34.4%	19.2%	15.4%
	Halved		16.2%	--	31.9%	--		20.8%	16.8%	26.7%	32.2%
Emergy Yield Ratio (EYR)	Doubled	1.31	1.54	--	--	--	3.23	--	1.53	--	--
	Halved		--	--	1.47	--		--	--	--	1.48
Environmental Loading Ratio (ELR)	Doubled	3.23	1.84	2.59	5.41	3.94	1.31	2.48	1.90	4.20	5.48
	Halved		5.17	3.68	2.14	2.87		3.80	4.95	2.74	2.10
Emergy Sustainability Index (ESI)	Doubled	0.41	0.84	0.54	0.22	0.32	0.41	0.57	0.80	0.29	0.22
	Halved		0.23	0.35	0.69	0.47		0.33	0.24	0.50	0.70
Emergy Efficiency Index (EEI)	Doubled	n/a	n/a				4.17E-02	--	3.58E-02	3.39E-02	2.72E-02
	Halved							--	--	4.71E-02	5.68E-02
Adjusted Yield Ratio (AYR)	Doubled	n/a	n/a				5.46E-02	--	--	4.19E-02	3.22E-02
	Halved							--	--	6.43E-02	8.37E-02

		Maryland Dairy Waste System			**Maryland AD System**				
Emergy Indice	**Emergy Transformation**	**Original Values**	Renewable Dairy Feed	Purchased Dairy Feed	**Original Values**	Renewable Feces	Renewable Urine	Purchased Feces	Purchased Urine
Proportion renewable (ΦR)	Doubled	13.1%	22.9%	7.4%	13.1%	20.3%	16.5%	8.2%	10.3%
	Halved		7.2%	21.4%		9.0%	11.3%	18.6%	15.1%
Emergy Yield Ratio (EYR)	Doubled	1.15	1.30	--	1.15	--	--	--	--
	Halved		--	1.27		--	--	--	--
Environmental Loading Ratio (ELR)	Doubled	6.61	3.36	12.47	6.64	3.93	5.07	11.19	8.69
	Halved		12.83	3.68		10.13	7.86	4.36	5.61
Emergy Sustainability Index (ESI)	Doubled	0.17	0.39	0.09	0.17	0.32	0.24	0.10	0.13
	Halved		0.08	0.35		0.11	0.14	0.28	0.21
Emergy Efficiency Index (EEI)	Doubled	n/a	n/a		7.81E-03	--	--	4.90E-03	6.16E-03
	Halved					--	--	1.11E-02	9.03E-03
Adjusted Yield Ratio (AYR)	Doubled	n/a	n/a		8.99E-03	--	--	5.33E-03	6.87E-03
	Halved					--	--	1.37E-02	1.06E-02

2.4 Discussion

The emergy analysis of the Haitian human waste digester and Maryland dairy waste digesters, including separate analyses of their food inputs and waste generation, demonstrated that the environmental sustainability of the anaerobic digestion systems depended heavily on the sustainability of the waste production systems feeding them. Food inputs accounted for 69.4% of all energy flows into the Haitian waste generation process, and 89.7% in the Maryland dairy system. Once delivered as feedstocks to the accompanying anaerobic digestion systems, the wastes were found to account for 99.8% of emergy inputs in the Haitian system and 99.6% in Maryland. In addition, all standard values and indices for each digestion system were found to closely resemble those of their parent waste generation system, highlighting the fact that a detailed analysis of the food inputs and waste streams preceding digestion, as conducted in this study, is necessary to determine accurate emergy values when accounting for entire waste treatment processes.

In terms of the overall environmental appropriateness of digester installation, the performance of anaerobic digestion systems based on comparisons of the emergy efficiency index (EEI) is decidedly mixed. The majority of the digestion systems, including the Maryland and Haitian systems analyzed in this study, do not provide sufficient yield equivalents to justify the emergetic investment made. However, these results must be evaluated in the context of competing waste treatment systems, whose effects on human health and the environment may be far more deleterious and resource intensive than anaerobic digestion.

2.4.1 Discrepancies in Emergy Accounting

In keeping with Ciotola et al. (2011), the separation of emergy inputs into renewable and non-renewable components was deemed to represent the most realistic method of approaching an emergy analysis. In considering the waste generation processes, the largest emergy-containing inputs were derived from the agro-industrial system, in which crops are produced as the result of renewable phenomenon (photosynthesis, rainfall, evapotranspiration, etc.) as well as non-renewable contributions (petroleum-based fertilizers, mechanical harvesters, etc.). Because labor derives its energy directly from these processes, it must be considered only partially renewable as well. However, this methodology is not standardized, and several of the studies used for comparison reported significantly better results in terms of environmental sustainability as a result of considering labor 100 % renewable.

For example, the proportion of renewable resource inputs (ΦR) for the Haitian and U.S. anaerobic digestion systems were 23.6% and 13.1%, respectively – the difference arising primarily due to the prevalence of raw and minimally processed foods in the Haitian diet. These values were lower than ΦR values for anaerobic digestion systems reported by three studies (78%, 87%, 66%) (Wei et al., 2009; Zhou et al., 2010; Ciotola et al., 2011), but higher than one reported value (0.03%) (Björklund et al., 2001). These results would indicate that the Haitian and U.S. systems are less capable of long-term, sustainable resource use than the majority of their counterparts. However, these results can be misleading due to the method of accounting employed by each study. Wei et al. (2009) and Zhou et al. (2010) included all animal feed, labor, and manure as 100% renewable, while Björklund et al. (2001) accounted all labor and energy inputs as 100%

non-renewable. Ciotola et al. (2011) calculated an ΦR of 93% for their Costa Rican digester if all inputs were considered entirely renewable. When all labor and manure inputs to the Haitian and U.S. digesters studied in this report were similarly calculated, the ΦR was 99.6% and 99.5%, respectively.

2.4.2 Emergy Indices

The EEI was developed to determine how well a given system's products justify the emergy expenditures used to create them. In this analysis, literature-based, equivalent solar transformities were used to evaluate the products of each anaerobic digestion system to provide an indication of how well the system creates exports that may otherwise be purchased from other sources (Tables 2-8 through 2-12). EEI values can also be used to more effectively isolate the efficiency of the system of interest, regardless of the efficiency of prior processes used to generate its inputs. In this study, the EEI of the Haitian system (0.0417) was approximately five times higher than the Maryland system (0.00782)(Table 2-7), demonstrating that while the Maryland system operates on a greater proportion of renewable inputs, those inputs may not be efficiently converted into viable products.

The AYR, developed to provide an index for a system's efficiency in its use of local and renewable resources, showed a similar difference between the two systems, indicating a more efficient digestion process in Haiti. This is partially the result of the heating demands of the Maryland digestion system, which require the use of around 31% of annual biogas production. It is also due to the higher relative contributions of purchased labor, electricity, and materials.

Not surprisingly, when comparing the Haitian and U.S. system using traditional emergy indices based on total inputs to the system as opposed to yield equivalents, the results were similar. The Haitian systems' efficiency in converting invested emergy into products (EYR) was greater than the Maryland system due to the relatively large contribution of renewable inputs contained in its waste. In the same manner, the emergy sustainability index (ESI) suggested a lower relative impact on the environment for the Haitian system.

When comparing the emergy indices of the Haitian and Maryland digestion systems to other anaerobic digesters, both systems initially seemed to perform poorly. Both the Maryland and Haitian digestion systems were comparatively inefficient in their use of purchased inputs (EYR), and had a roughly six and thirteen-fold greater burden on the environment, respectively, than the Costa Rican system. The emergy sustainability index likewise suggested poor environmental sustainability for the Haitian and U.S. systems in comparison to their counterparts. However, due to the differing accounting methodologies employed by the previous studies, especially in terms of the renewability of waste and labor, traditional emergy indices were not seen as a valid indicator of environmental sustainability when comparing anaerobic digestion systems in this report. The EEI and AYR were created in part to address this, and a comparison of digestion systems based on these indices indicates that the Haitian and Maryland systems provided lower returns in terms of reusable products per unit of investment than the Costa Rican and Chinese digesters (Table 2-7).

2.4.3 Transformities of Biogas

Transformities calculated for the products of a given system are often compared to similar systems as another measure of the efficiency with which system inputs are converted to exports. Low transformities are indicative of an efficient process, as small emergetic inputs are required to produce a given quantity of material. On that basis, the Haitian and U.S. anaerobic digestion systems proved inefficient in the production of biogas compared to their counterparts (Figure 2-7).

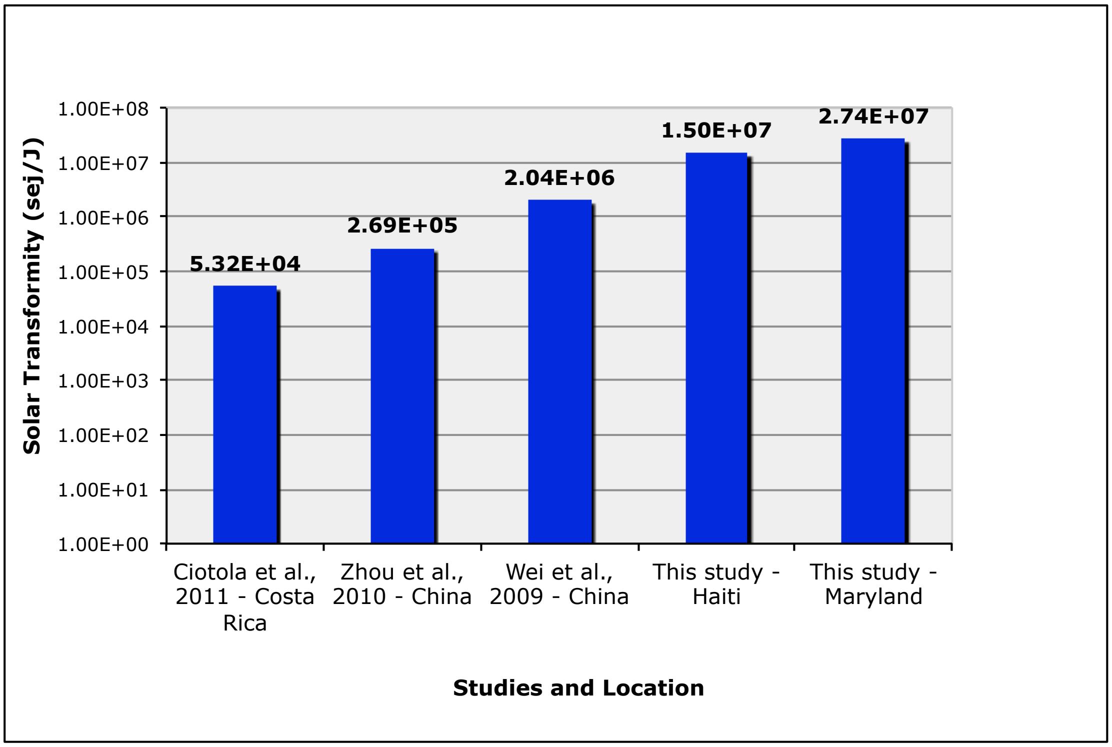


Figure 2-7 - Biogas transformities for anaerobic digesters

These results can be traced to two primary factors: scale and climate. The 12 m^3 Haitian anaerobic digestion systems used 7.98E+17 sej/year to produce 5.32E+10 J/year of biogas, with a productivity of 4.43E+09 J/m^3. By contrast, the 15.6 m^3 Maryland digester used 1.84E+18 sej/year to produce 6.74E+10 J/year biogas, yielding a productivity of 4.32E+09 J/m^3 – about 3% less methane yield per cubic meter of digester capacity than the Haitian system. The Maryland system's slightly lower energy production was primarily the result of its heating requirements. The Costa Rican bag digester (Ciotola et al., 2012) had a capacity of 146 m^3, converting 1.59E+16 sej/year of emergy into 2.99E+11 J/year of biogas for a transformity of 5.32E+04 sej/J, and gaining efficiency from a warm climate (heating from solar insolation only) and small inputs of building materials. It yielded 2.05E+09 J/m^3 of digester capacity – less than both the Haitian and Maryland systems – illustrating the important difference between energy efficiency and *emergetic* efficiency. In comparison, the Chinese digesters investigated by Zhou et al. (2010) were 200 m^3 and 500 m^3 reactors requiring supplemental heating and comparatively large material inputs. They converted 1.48E+18 sej/year of inputs to 5.50E+12 J/year biogas for an output of 7.86E+09 J/m^3, but at a slightly higher transformity than the Costa Rican system (2.69E+05 sej/J). The 8 m^3 digester analyzed by Wei et al. (2009) also required heating and produced 6.28E+09 J/year biogas from 1.28E+16 sej/year of inputs for an output of 7.85E+08 J/m^3 and a transformity of 2.04E+06 sej/J, its lower biogas transformity and production per unit area are the result of heating requirements and relatively high material inputs per cubic meter of digester capacity. The difference between biogas transformity and energy output per unit area of digester space illustrates the importance of suitable digester sizing, as well as the selection of material inputs with low emergy transformities/densities during the construction of an anaerobic digestion system.

2.4.4 Joint Transformities

Although biogas is generally viewed as the primary product of anaerobic digestion processes, comparing system productivity based on biogas production alone provides an incomplete perspective. Together with the EEI, the joint transformity, developed by Bastianoni and Marchettini (2000), allows for comparisons between similar systems based on the ratio of the energy annually contained within their co-products to the overall annual emergy inputs used to create them. Biogas, nitrogen, phosphorous, and water were produced in the Haitian digestion systems, while the Maryland digester produced those products in addition to bedding. Although water was included in the emergy analysis of these two systems as a co-product, no other study on anaerobic digestion has reported water in the same manner; for this reason, water production was not included in the calculation of joint transformity in this report. Where emergy densities were calculated instead of solar transformities (sej/g reported instead of sej/J), the Gibbs free energy of the material was used to establish that material's energy content (Odum, 1996). In this report, the Gibbs free energy for nutrients was taken from Zhou et al. (2010) in order to facilitate comparison amongst systems, as Ciotola et al. (2011) had used the same methodology in their study. The use of the joint transformity clearly showed the benefit of co-production in each of the anaerobic digestion studies, although the improved emergy input to energy output ratio was most pronounced in the Wei et al. and Maryland system. The Maryland system's joint transformity was reduced by a factor of three from its biogas transformity due to the energy inherent in its bedding product, while the Haitian system was essentially unchanged, due to the relatively low level of nutrients produced from the system. By contrast, the Wei et al. system proved much more emergetically efficient due to its diverse output of biogas, peach trees, peach branches, and swine.

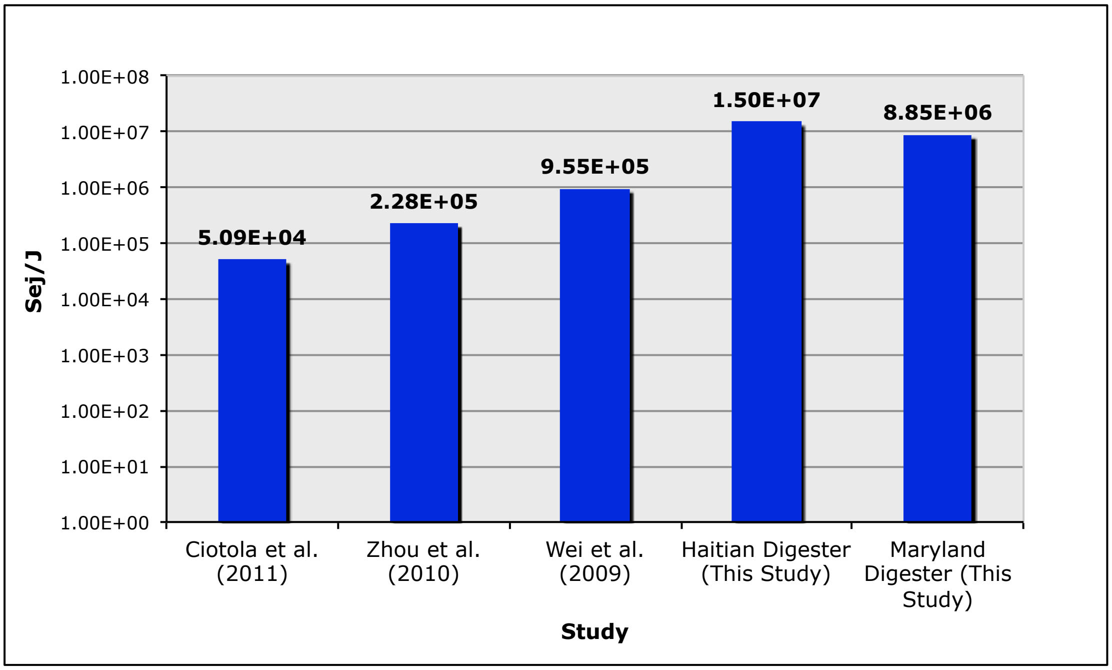


Figure 2-8 - Joint transformities for the products of various anaerobic digestion systems

The Costa Rican system produced larger levels of nutrients than either the Haitian or Maryland digesters, and showed lower joint transformities as a result. Similar to the EEI, these findings underscore the improved efficiency gained from the production of multiple commodities, and both accounting methods provide a rationale for attempting to find viable uses for wastes.

2.4.5 Zeroing the Contribution of Waste

While this study has chosen to account for the emergetic inputs to anaerobic digestion systems by conducting a holistic analysis of diets, waste generation, and digestion processes, it may be equally appropriate to analyze and compare systems at a more microscopic scale. A broadly defined analysis of anaerobic digestion has the benefit of drawing attention to the sustainability (or lack thereof) of the food production and waste generation systems feeding digestion systems. However, if one is interested solely in digester-related infrastructure and products, a more local focus can help illuminate differences. Vieira and Domingos (2004) have proposed the attribution of all emergy held in wastes to the processes that created them, thereby effectively zeroing the solar transformities of waste in emergy accounting, and assigning the products of waste treatment processes the emergy of those processes alone. Tables 2-14 and 2-15 show the result of this approach on the two Haitian and Maryland anaerobic digestion system analyses. The heavy dependence of the Maryland system on electricity (for heating) and labor (for design and construction) immediately become apparent, and the system's renewable emergy inputs relative to the Haitian digestion system decrease as a result (2.0% versus 22%). In addition, the ELR increased significantly for the Maryland system (48.4, versus 3.50 for Haiti), and the ESI dropped (0.021 versus 0.37). Predictably, the AYR and EEI increase due to decreased overall emergy inputs to the system, and transformities for biogas improve, making them competitive with traditional fuels (Table 2-16). When compared to other anaerobic digestion systems with waste inputs zeroed, biogas transformities for both the Haitian and Maryland system became competitive (Figure 2-9). The Haitian system had the second lowest biogas transformity of all digestion systems (3.35E+04 sej/J), while the Maryland system's transformity proved lower than the digester analyzed by Wei et al. (2009)(1.90E+06 sej/J). In addition, these transformities proved lower than competing energy production systems, including biodiesel production and electricity generation from coal and geothermal heat. At this reduced scope, the differences exhibited between the broad-spectrum analysis also illustrate the importance of climate on relative environmental sustainability. The Maryland digester and Wei et al. (2009) system both operate in temperate climates with cold winters, and their biogas transformities more clearly reflect this fact with waste inputs zeroed.

Table 2-14 - Emergy table for the Haitian digestion system – waste inputs zeroed

#	Item	Unit	Amount Per year	Solar Transformity (sej/unit)	Ref. for Transf.	Solar Emergy (sej/yr) E12	% Contribution to Total
Renewable Resources [R]							
R1	Solar Radiation	J	3.11E+08	1.00E+00	By definition	3.11E-04	0.0%
R2	Conveyance Water (Groundwater)	g	2.13E+08	1.14E+06	a	2.43E+02	13.6%
R3	Labor & Maintenance	J	1.53E+07	1.00E+07	b	1.53E+02	8.6%
R4	Human feces	g	0.00E+00	4.36E+09	e	0.00E+00	0.0%
R5	Human urine	g	0.00E+00	4.36E+09	e	0.00E+00	0.0%
Total [R]						**3.96E+02**	**22.2%**
Purchased Resources [P]							
P1	Labor & Maintenance	J	8.41E+07	1.00E+07	b	8.41E+02	47.2%
P2	Biodigester Bags (PP)	g	5.60E+03	9.86E+09	d	5.52E+01	3.1%
P3	Influent & Effluent Piping (PVC)	g	4.98E+04	9.86E+09	d	4.91E+02	27.5%
P4	Human feces	g	0.00E+00	4.36E+09	e	0.00E+00	0.0%
P5	Human urine	g	0.00E+00	4.36E+09	e	0.00E+00	0.0%
Total [P]						**1.39E+03**	**77.8%**
Total Emergy Inputs [I]						**1.78E+03**	**100.0%**
Yield [Y]							
Y1	Biogas	J	5.32E+10	3.35E+04	This report	1.78E+03	100.0%
Y2	Total Nitrogen	g	1.30E+06	1.37E+09	This report	1.78E+03	100.0%
Y3	Total Phosphorus	g	3.03E+05	5.88E+09	This report	1.78E+03	100.0%
Y4	Non-potable water	g	3.65E+08	4.88E+06	This report	1.78E+03	100.0%

a) Buenfil, 2001; b) Odum, 1996, corrected by a factor of 1.68 (Odum et al., 2000); c) Haukoos, 1995; d) Pulselli et al., 2007; e) This report; f) Bastianoni et al., 2009

Table 2-15 - Emergy table for the Maryland digestion system – waste inputs zeroed

#	Item	Unit	Amount Per year	Solar Transformity (sej/unit)	Ref. for Transf.	Solar Emergy (sej/yr) E12	% Contribution to Total
Local Renewable Resources [R]							
R1	Solar Radiation	J	3.21E+08	1.00E+00	By definition	3.21E-04	0.0%
R2	Labor & Maintenance	J	1.58E+07	1.00E+07	a	1.58E+02	2.0%
R3	Feces	g	0.00E+00	9.60E+09	b	0.00E+00	0.0%
R4	Urine	g	0.00E+00	9.60E+09	b	0.00E+00	0.0%
Total [R]						**1.58E+02**	**2.0%**
Purchased Resources [P]							
P1	Electricity	J	3.73E+09	5.64E+05	a	2.11E+03	26.9%
P2	Labor & Maintenance	J	3.07E+08	1.00E+07	a	3.07E+03	39.3%
P3	Cast iron cased pumps	g	5.42E+03	1.74E+09	c	9.44E+00	0.1%
P4	Diesel	g	9.45E+03	2.83E+09	d	2.67E+01	0.3%
P5	Insulative nests (EPS)	g	2.59E+03	8.85E+09	e	2.29E+01	0.3%
P6	Hot water piping (PEX)	g	7.91E+02	8.85E+09	e	7.00E+00	0.1%
P7	Culverts (HDPE)	g	4.10E+04	8.85E+09	e	3.63E+02	4.6%
P8	Feces	g	0.00E+00	9.60E+09	b	0.00E+00	0.0%
P9	Urine	g	0.00E+00	9.60E+09	b	0.00E+00	0.0%
P10	Piping (PVC)	g	4.87E+03	9.86E+09	e	4.80E+01	0.6%
P11	Digester Bags (PVC)	g	3.48E+03	9.86E+09	e	3.43E+01	0.4%
P12	Solids Separator	g	2.50E+04	2.85E+10	c, e	7.13E+02	9.1%
P13	Stainless steel heating kettle	g	2.07E+04	5.53E+10	e, f	1.14E+03	14.6%
P14	Copper wiring	g	8.98E+02	9.80E+10	f	8.80E+01	1.1%
P15	Bronze cased pumps	g	1.36E+02	2.94E+11	f	4.01E+01	0.5%
Total [P]						**7.67E+03**	**98.0%**
Total Emergy Inputs [I]						**7.83E+03**	**100.0%**
Yield [Y]							
	Biogas	J	6.74E+10	1.16E+05	This study	7.83E+03	
	Total Nitrogen	g	3.64E+05	2.15E+10	This study	7.83E+03	
	Total Phosphorous	g	4.84E+04	1.62E+11	This study	7.83E+03	
	Bedding	g	8.41E+06	9.31E+08	This study	7.83E+03	
	Non-potable water	g	1.80E+08	4.36E+07	This study	7.83E+03	

a) (Odum, 1996) corrected by factor of 1.68 (Odum et al., 2000); b) This study; c) Haukoos, 1995; d) Bastianoni et al., 2009; e) Pulselli et al., 2007; f) Cohen et al., 2007

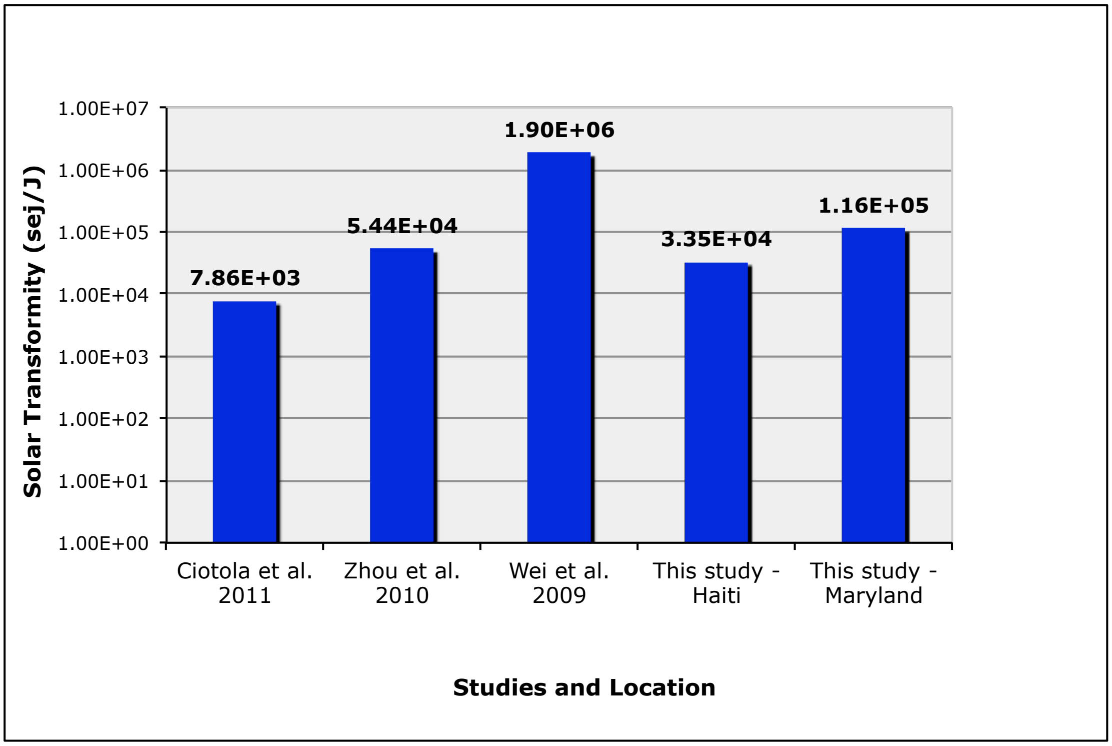


Figure 2-9 - Biogas transformities for anaerobic digesters – waste inputs zeroed

2.4.6 Comparison to Other Renewable Energy Production Systems

In order to assess the performance of the two anaerobic digestion systems analyzed in this study in contrast to other energy production systems, the biogas transformities derived from the Haitian and Maryland systems were compared to the solar transformities of various energy sources (Table 2-9). Both systems performed poorly in terms of emergy investment per unit of energy return. This finding further insinuates that the Haitian digester may have been inappropriately sized, and emphasizes the Maryland digester's inefficiency due to large biogas heating requirements. In particular, comparisons of all anaerobic digesters to equivalent energy sources (i.e. natural gas) show that the systems' biogas transformities are higher than comparable fuels, and are at least an order of magnitude higher in the case of the Haitian and Maryland systems. Combined with the AYR values, these findings indicate that the construction of the investigated anaerobic digesters for biogas production alone is an inappropriate use of resources. However, when combined with the indeterminate benefits of waste treatment and improved nutrient availability of digestate for plant uptake, greenhouse gas emission reductions and odor control, digestion systems may indeed prove sustainable.

Further evidence of the environmental sustainability of anaerobic digestion has been provided by Life Cycle Analyses (LCAs). Unlike emergy analyses, LCAs factor into their analysis the effect of eutrophication, greenhouse gas emissions, acidifying emissions from biogas combustion (NOx and SO_2), the fate of carcinogens, human health, and other eco-indicators. Özeler et al. (2006), Chaya and Gheewala (2007), and Cherubini et al. (2009) have shown anaerobic digestion to have less environmental loading than landfilling and incineration for various municipal solid wastes, and also showed anaerobic digestion to be one of the best waste treatment technologies for the reduction of greenhouse gas emissions as compared to standard practice.

Finally, despite the near-term boom in natural gas development, gas prices are expected to rise over the next decades (Paltsev et al., 2011; Shafiee and Topal, 2009) and resource extraction already poses a number of problems that may increase the intensity of mining (Kargbo et al., 2010). This is likely to lead to increased emergy expenditures in the production of natural gas, increasingly tipping the balance towards anaerobic digestion as a viable, environmentally sustainable fuel source.

Table 2-16 - Comparison of solar transformities for various energy sources

System	Product	Transformity (sej/J)	Reference
Solar	Heat	1.58E+04	Paoli et al. (2008)
Coal	Coal	4.00E+04	Odum (1996)
Petroleum natural gas	Methane	4.35E+04	Bastianoni et al. (2005)
Natural gas	Methane	4.80E+04	Odum (1996)
Sugarcane, Brazil	Ethanol	4.87E+04	Pereira and Ortega (2010)
Natural gas	Methane	5.22E+04	Bargigli et al. (2004)
EARTH University	Biogas	5.32E+04	Ciotola et al. (2011)
Crude oil	Oil	5.40E+04	Odum (1996)
Oil	Oil	5.42E+04	Bastianoni et al. (2005)
Wind	Electricity	6.21E+04	Brown and Ulgiati (2002)
Hydro	Electricity	6.23E+04	Brown and Ulgiati (2002)
Haiti digester (waste zeroed)	**Biogas**	**8.84E+04**	**This Study**
Solar	Electricity	8.92E+04	Paoli et al. (2008)
Energy crops	Methane	8.94E+04	Jury et al.
Heat from Straw	Heat	1.04E+05	Nilsson (1998)
Geothermal	Electricity	1.47E+05	Brown and Ulgiati (2002)
Coal power plant	Electricity	1.60E+05	Odum (1996)
Methane	Electricity	1.70E+05	Brown and Ulgiati (2002)
Coal	Electricity	1.71E+05	Brown and Ulgiati (2002)
Maryland digester (waste zeroed)	**Biogas**	**1.98E+05**	**This Study**
Oil	Electricity	2.00E+05	Brown and Ulgiati (2002)
Sunflower seed	Biodiesel	2.31E+05	Giampietro and Ulgiati (2005)
Dairy farm, Puerto Rico	Methane	2.48E+05	Bastianoni and Marchettini (2000)
Farm biogas project	Biogas	2.69E+05	Zhou et al. (2010)
Soybean	Biodiesel	3.90E+05	Cavalett and Ortega (2010)
Dairy farm, Puerto Rico	Electricity	1.19E+06	Bastianoni and Marchettini (2000)
EARTH University	Electricity	1.59E+06	Ciotola et al. (2011)
FIOPPS	Biogas	2.04E+06	Wei et al. (2009)
Haiti digester	**Biogas**	**1.50E+07**	**This Study**
Maryland digester	**Biogas**	**2.74E+07**	**This Study**

2.5 Conclusions

This study used emergy accounting to evaluate two anaerobic digestion systems by quantifying all inputs into a common-denominating unit – the solar emjoule. The study underscored the difficulty in disentangling waste treatment processes from their contributing waste streams and highlighted the connection between the sustainability of waste treatment systems and the waste production systems that feed them. The relative environmental sustainability of the Haitian digestion system compared to the Maryland digester, as indicated by the EYR, ELR, and ESI, demonstrated the degree to which an anaerobic digestion system can be affected by the renewable composition and energy content of the waste stream that it treats.

However, the improved sustainability of the Maryland system when viewed from the perspective of its joint transformity showed the importance of assessing similar systems using a variety of approaches. Although demonstrating a relatively low burden on the surrounding environment, the Maryland digester was deemed less appropriate at its designed scale than the Haitian system due to its low EEI and AYR, indicating the outputs produced could be more sustainably purchased than created in the anaerobic digestion system. Although other anaerobic digestion systems appear to be more appropriate than both digesters analyzed in this study, methane production as the sole basis for construction of anaerobic digesters appears unsustainable amongst all systems analyzed. While co-production of multiple products seems to improve the environmental viability of digesters, further emergy studies on anaerobic digestion systems and biogas production are needed to assess the environmental sustainability of these systems, especially small-scale systems in temperate climates.

Efforts were made during this study to compare only similar systems when collecting data from the literature. For this reason, only systems creating biogas as their primary product were considered, and no operations that converted biogas to electricity or any other product were taken into account. The refinement of biogas for electricity generation has been found to significantly increase emergy inputs and decrease environmental sustainability (Björklund et al., 2001; Ciotola et al., 2011). In western settings, and in many other systems through the developing world, electricity or refined biogas is the desired product from anaerobic digestion systems (Holm-Nielsen et al., 2009; Mshandete and Parawira, 2010; Mueller, 2007). For this reason, the findings of this study should be used with the understanding that the actual use of biogas may incur much higher emergy expenditures.

There is a very clear need to standardize the emergy accounting procedures for anaerobic digestion systems, as varying assessments of waste and labor inputs make comparison amongst systems difficult, and may introduce bias into the analyses. The emergy efficiency index (EEI) was introduced as a means to assess the appropriateness of anaerobic digestion infrastructure and reduce bias amongst digestion studies. The findings of this study highlight the importance of attention digester scale and the importance of modeling digesters designed for temperate climates to ensure their environmental suitability. Furthermore, when judged by the EEI, anaerobic digestion systems cannot be categorically labeled as environmentally sustainable, at least when judged from a purely production-oriented perspective. Further studies are needed to determine the conditions in which their construction and use can be deemed appropriate, especially in terms of their effect on human and environmental health and greenhouse warming when compared to traditional means of waste treatment.

3 WASTE TREATMENT AND ENERGY PRODUCTION OPTIONS RESULTING FROM THE FRACTIONATION OF A DAIRY MANURE WASTE STREAM

3.1 Introduction

Proper waste treatment is of increasing concern throughout the world as a growing population creates larger waste streams which, in turn, impose increasing demands on water, environmental, and capital resources (UNEP and UN-HABITAT, 2011). At the same time, burgeoning populations are placing increased pressure on energy supplies (Brown et al., 2011), and there is a growing recognition that improved energy efficiency, reduced consumption, recycling of nutrients, and alternative energies will be necessary components of future planning (Brown et al., 2011; Krewitt et al., 2009).

Anaerobic digestion provides a means to simultaneously address waste treatment and renewable energy production, and is frequently used to treat waste, reduce greenhouse gas emissions, and produce renewable energy and fertilizer (Clemens et al., 2006; Lusk et al., 1996; Mata-Alvarez et al., 2000; Müller, 2007). Anaerobic digestion is a process through which microbial communities biodegrade organic wastes into biogas – a mixture consisting of methane, carbon dioxide, and other trace gases – in an oxygen-free environment. Digestion is governed by a broad consortium of microorganisms, including methanogens, which reduce organic wastes into two primary end-products: methane-enriched biogas, and a nutrient-rich, liquefied slurry commonly referred to as digestate.

3.1.1 Transformations of Organic Solids and Nutrients During Digestion

During the anaerobic digestion process, microbial activity results in the breakdown of volatile organic solids (VS) and the creation of biogas. Reductions of 20-65 % VS and biogas production of 0.75–1.0 m^3/kg VS can generally be expected at mesophilic temperatures, depending on the type of waste (Ciborowski, 2001; Gerardi, 2003; Lusk, 1998). At the same time, organically-bound nutrients are mineralized as bacteria breakdown and metabolize organic substrates into increasingly simplistic molecular fractions. This typically results in an increase in soluble nutrient species and, due to the anaerobic environment, a decrease in oxidized forms. The increase in ammonium-N and orthophosphate-P concentrations in wastes undergoing anaerobic digestion is well established (Martin, 2005; Schievano et al., 2011; U.S. National Academy of Sciences, 1977). The loss of reduced gaseous nutrient species are common (NH_3, H_2S, H_2), but account for minimal overall losses except in the case of hydrogen sulfide (Schievano et al., 2011, 2011). Therefore, nutrient speciation changes as a result of anaerobic digestion, but total nutrient concentrations are generally conserved (Ciborowski, 2001).

3.1.2 Agricultural Nutrient Management

In the United States, much of the emerging anaerobic digestion industry is focused on agricultural livestock operations, which produce over five-hundred million tons of manure annually (USEPA, 2005). Proper nutrient management of these waste streams has become a subject of concern due to the threat of increased point-source pollution resulting from large-scale, concentrated animal operations (Kellogg et al., 2000) and a general expansion of regulatory oversight of nutrient loading on the environment (Branosky et al., 2011; Rasmussen and Adams, 2004). Numerous state and federal regulatory agencies mandate the implementation of nutrient management plans on farms (Beegle and Martin, 2010; Meyer et al., 2011; Rasmussen and Adams, 2004), and farmers incorporating anaerobic digestion systems into their operations are increasingly required to catalogue the resulting transformations to nutrient flows (Pentzer, 2008).

In 2009, the U.S. EPA announced its intent to regulate nutrient loading into the Chesapeake Bay under a watershed-wide total maximum daily load (TMDL) standard for nutrients and sediment (USEPA, 2011). Under the EPA's plan, a series of two-year milestones are being set with the input of Chesapeake Bay watershed states, each imposing more stringent environmental regulations on farms and other pollution sources through the year 2017 (USEPA, 2011). Aside from direct regulatory action by federal and state governments, farms must also consider the potential for civil suits under the same regulations (U.S. District Court, 2010). These developments have led to the increased use of nutrient management plans, which are formulated to consider all nutrient flows from animal wastes, wastewater, fertilizer amendments, crop residues, and N-fixation, amongst others (NRCS, 2006).

As anaerobic digestion technology is incorporated onto farms in the Chesapeake Bay Watershed area and in other areas throughout the country, nutrient management will be of central concern. While nutrient loads are not significantly diminished as a result of the anaerobic digestion process, the process may provide a significant contribution to nutrient reduction plans due to its ability to reduce organic solids and convert nutrients, especially nitrogen, into more soluble, plant-available forms (Álvarez et al., 2008; Lukehurst et al., 2010; Schievano et al., 2011).

3.1.3 Alternative Management of Agricultural Digesters

Currently, 191 anaerobic digesters exist for agricultural waste treatment in the United States – the majority operating as complete mix and horizontal plug flow systems treating dairy manure (AgSTAR, 2012). In conventional U.S. cattle operations where an anaerobic digester is used, raw manure – often including bedding material – is washed or scraped into holding pits or lagoons where it is either transferred to a digester or digested in-situ (e.g. covered lagoons). In the majority of U.S. agricultural digester operations, the manure solids and bedding are separated via screen or screw-press separators in post-digestion operations (Kramer, 2009; Scott et al., 2010). Because total nitrogen, phosphorus, and potassium levels are only minimally reduced by the digestion process, the digestate provides a relatively easily applied, effective liquid fertilizer (Allan et al., 2003; Hjorth et al., 2009; Lukehurst et al., 2010; Schievano et al., 2011).

In contrast, there are some digestion operations in the US and other areas of the world where most of the bedding and manure solids are settled or screened out prior to digestion in order to prevent non-biodegradable constituents from entering and accumulating in the digester (Lukehurst et al., 2010; Scott et al., 2010; Vízquez Arias, 2009). Due to the removal of solids, anaerobic digesters operating within these farming systems are generally smaller, meaning infrastructure costs may be lower. Additionally, the screened solids may be transferred to composting facilities, yielding a product with lower nutrient levels and higher levels of complex organic constituents, such as humic and fulvic acids (Brito et al., 2008; Inbar et al., 1990). When used as a soil amendment, these compost products may improve soil structure and provide for greater long-term nutrient retention (Bar-tal et al., 2004; Brito et al., 2008).

3.1.3.1 High-Solids Anaerobic Digestion

Another alternative method of anaerobic digestion is dry and high-solids (>15%) digestion. This process has lower space requirements due to minimal moisture content and offers potentially reduced waste transportation costs (Schäfer et al., 2006). Numerous studies have explored high-solids digestion. (Hills, 1980) and (Hall et al., 1985) were amongst the first to study high-solids digestion, finding 50-60% methane production from dairy manure and mixed substrates. (Kayhanian and Hardy, 1994) and (Kayhanian and Rich, 1995) found balanced levels of micronutrients to be important to the process, and discovered that moderately-sized (5 cm) organic substrates, C/N ratios typical of composting (~30/1), low organic loading rates (7 g VS/kg), and moderately long retention times (30 days) were ideal for high-solids digestion. (Martin and Xue, 2003) have explored microbial kinetics involved in high-solids digestion, highlighting the importance of a viable seed bed (inoculated organic mass) in high-solids digestion, and (Vavilin et al., 2003) have similarly reported on the positive effect of leachate recirculation.

Recent research into high-solids digestion has been particularly focused on food waste and MSW (Drennan and DiStefano, 2010; Forster-Carneiro et al., 2008; Guendouz et al., 2010; Lopes et al., 2004; Schievano et al., 2010), and there seems to be relatively little interest in the potential of high-solids digestion for agricultural and dairy applications. (Ahn et al., 2010) found poor performance from the dry co-digestion of high solids dairy manure and switchgrass compared to co-digesting switchgrass and swine manure, mainly due to a buildup of volatile fatty acids and a drop in pH. (Li and Wang, 2011) explored the effect of total solids loading rates and mixing on high-solids digestion of cattle manure, and found methane concentrations of ~50 % in biogas with moderate, bi-daily agitation.

3.1.4 Research Objectives

This research seeks to more fully explore the suitability for digestion of the various fractions of dairy manure, as well as the implication of digestion on farm nutrient management. The primary objective of this research is to provide an overview of waste treatment and energy production options provided by anaerobic digestion using dairy manure collected at the Beltsville Agricultural Research Center (BARC) in Beltsville, MD, as a proxy. In this study, two biochemical methane production (BMP) analyses were conducted: the first BMP explored digestion production and transformation of various fractions of dairy manure from BARC, including scrapped manure, the liquid fraction and solid fraction after separation, the digester effluent, and the post-digestion lagoon. The second BMP investigated the methane potential and nutrient transformations of separated and dried (50 % moisture content), separated high-solids manure. In addition, varying inoculum ratios in high-solids digestion were explored in BMP #2. Solids and nutrients data were collected before and after each BMP, and tested for nutrient transformations, specifically carbon (C), nitrogen (N), phosphorus (P), and potassium (K). This information may be used by farmers to development nutrient management plans that accommodate anaerobic digestion systems, allowing for an improved understanding of available options, as well as an improved ability to comply with current and future environmental regulations.

3.2 Materials and Methods

3.2.1 Site Description

All manure samples were collected from the USDA's dairy facility and associated small-scale continuous stirred-tank reactor (CSTR) anaerobic digester at the USDA-ARS Beltsville Agricultural Research Center dairy facility in Beltsville, Maryland (39º1'47" N latitude, 76º53'27" W longitude; elevation: 34 m). The climate is temperate, with mean temperatures in January and July of 1.4 ºC and 25.8 ºC, respectively (NOAA, 2011b).

The BARC dairy houses 105 milking cows, with approximately 10 dry cows at any given time. Lactating cattle are housed continuously in a free-stall barn bedded with wood chips. Cows are fed a diet consisting of corn silage (~40%), ground corn grain (~19%), alfalfa silage (~16%), whole soybean (4%), and soybean meal (4%), with the remainder comprised of protein supplements, vitamins, and sugar (Table 2-2). Manure is scraped continuously to a holding pit, from which it is pumped to the CSTR digester.

3.2.2 Sampling of Manure Substrates

Samples were gathered in accordance with (Peters et al., 2003) from each of the following substrates: (1) scraped manure from the dairy manure pit; (2) the separated liquid fraction of the manure derived from a mechanical screw-press separator; (3) the separated solid fraction of the manure from the screw-press separator; (4) inoculum (control) from the onsite CSTR digester; (5) the digester effluent from the onsite CSTR digester; (6) and the post-digestion treatment lagoon slurry. All samples were transported on ice to the University of Maryland Water Quality Laboratory and stored at 4 ºC prior to pH, alkalinity, solids, and BMP-testing or at -20 ºC prior to nutrient analysis. All samples were collected from their respective fractions of the dairy waste stream in 3 L, acid-washed, polyethylene containers (APHA, 2005).

3.2.3 Biochemical Methane Potential (BMP) Trials

Biochemical Methane Potential (BMP) trials are controlled tests used to assess the methane production potential of a given organic waste. For the first BMP analysis, all fractions of the BARC dairy waste stream, as described above, were tested via a slight variation of the methods proposed in (Moody, 2010). Each 3 L sample was homogenized, and three sub-samples were extracted and mixed with inoculum based on their volatile solids content (Table 3-1). For the second BMP trial, two substrates were tested: the solid fraction of the separated manure and the solid fraction of the separated manure after being dried at 50 ºC to approximately 50% moisture content. These two substrates were prepared with three different ratios of inoculum (Table 3-2). All assays were conducted in 250 mL borosilicate glass serum bottles capped by self-sealing rubber sleeve stoppers. All serum bottles were filled with

Table 3-1 - Experimental design for BMP Trial #1

Test Material	Avg. Test Material (g)	Avg. Inoculum (g)	Avg. Proportion Test Material	Number of Samples
Inoculum	0.00	200.02	0.00	3
Scraped manure	31.93	168.08	0.16	3
Separated liquid manure	61.02	139.06	0.30	3
Post-treatment lagoon	126.11	73.94	0.63	3
Digester effluent	111.13	88.90	0.56	3

Table 3-2 - Experimental design for BMP trial #2

Test Material	Avg. Test Material (g)	Avg. Inoculum (g)	Avg. Proportion Test Material	Number of Samples
Separated solid manure - 0% Inoculum	29.99	0.00	1.00	3
Separated solid manure - 20% Inoculum	23.85	6.21	0.79	3
Separated solid manure - 33% Inoculum	19.94	10.06	0.66	3
Dried (50% MC) separated solid manure - 0% Inoculum	30.01	0.00	1.00	3
Dried (50% MC) separated solid manure - 20% Inoculum	23.98	6.03	0.80	3
Dried (50% MC) separated solid manure - 33% Inoculum	20.04	10.01	0.67	3

their respective substrate, purged with an 80:20 N_2 to CO_2 gas mixture for one minute, and promptly capped. All sample bottles were then placed on a platform shaker (Innova 2300, New Brunswick Scientific) revolving at 120 rpm and incubated for 30 days in an environmental chamber at 35 ºC. In order to avoid the development of excessive pressure in the bottles, biogas production was measured via gas-displacement using a graduated 50 mL volumetric glass syringe with 2 mL gradations at intervals of two times per day for Days 1-3, daily for Days 4-9, every two days for Days 10-20, and every three days for Days 21-34. For BMP #2, the biogas production was also tested as detailed above, in addition to every 4-7 days for Days 35-61. Rubber stoppers were sealed with silicon at previous injection sites after each sampling interval. Samples of 0.1 mL were drawn from the collected biogas and analyzed for methane via FID gas chromatography (Agilent 5900 GC) with an injection temperature of 200 °C, a detector temperature of 250 °C, and helium used as the carrier gas at a flow rate of 300 ml/min.

The average daily biogas and methane production of the control was subtracted from each substrate bottle to account for gas production attributed to the inoculum in each bottle. When calculating total methane production, gas volumes were normalized by the volume of production per gram of substrate and per gram of VS, as farmers generally manage their waste by volume or mass, while industry standards call for normalization and comparison of data based on VS (AgSTAR, 2011). In addition, (Moody et al., 2011)recommended normalizing based on VS for agricultural wastes due to the variability associated with COD in high-solids materials.

3.2.4 Analytical Methods

All manure samples in the BMP trials were analyzed before and after the trials. Pre-digestion samples of each individual substrate were analyzed within 24-hours of collection, and post-digestion composite bottles were analyzed within 24-hours following the end of the BMP. Moisture content (MC), total solids (TS), and volatile solids (VS) were measured following Standard Methods (APHA, 2005) by drying samples at 105 ºC for 24 hours and then combusting at 550 ºC for 20 minutes (APHA, 2005). Alkalinity and pH were measured in following with the Recommended Methods of Manure Analysis and Standard Methods (APHA, 2005; Peters et al., 2003). Both alkalinity and pH were evaluated using a laboratory pH meter (Accumet AB15+), and solid manure samples were analyzed using a 1:2 dilution of manure to deionized water. Total carbon (TC) and total nitrogen (TN) were assessed using an elemental analyzer (Elementar Vario Max CNS), and total kjeldahl nitrogen (TKN) and total phosphorus (TP) were analyzed using an acid digestion procedure detailed in the Recommended Methods of Manure Analysis (Peters et al., 2003). Total potassium (TK) was analyzed using microwave assisted acid digestion and was measured using ammonium-N colorimetry (Peters et al., 2003). Orthophosphate $\left(PO_4^{3-}\right)$ and ammonium (NH_4^+) were charcoal filtered to 0.45µm and analyzed colorimetrically using a Latchat QuikChem 8500 Series 2 FIA system.

3.2.5 Statistical Analysis

Univariate analysis of variance (ANOVA) analysis followed by a post hoc Tukey HSD test were used for multiple comparisons of means to determine differences in biomethane potential, solids composition, and nutrient levels between manure substrates.

A paired Student's t-Test was applied to solids and nutrient values measured before and after anaerobic digestion to test for significant differences between influent and effluent values for treatment sets. For all statistical analyses, p-values < 0.05 were deemed significant; differences in multiple means comparisons were considered significant at alpha = 0.05.

3.3 Results

3.3.1 BMP #1: 35-day Liquid Manure BMP Trials

The pre- and post-digestion characteristics of the test substrates for BMP #1 are shown in Table 3-4. A series of one-way between subjects ANOVAs indicated that significant differences existed between waste types with respect to biogas production, methane production, methane content in the biogas, TS, VS, and C/N, as detailed below.

3.3.1.1 Gas Production

Table 3-3 - Solids destruction and gas production in BMP #1 (+/- SEM; n=3)

Value	Scrapèd Manure	Separated Liquid Manure	Digester Effluent	Post-Treatment Lagoon	Inoculum
Initial VS (mg/g)	48.6 +/- 7.77	30.5 +/- 0.645	11.0 +/- 0.249	12.0 +/- 0.583	12.0 +/- 0.177
VS Destroyed (%)	35% +/- 16%	54% +/- 2.9%	3.2% +/- 6.4%	6.4% +/- 3.7%	13% +/- 2.0%
Cumulative Biogas/Substrate (ml/g)	16^{A} +/- 0.52	8.4^{B} +/- 1.6	0.27^{C} +/- 0.005	0.28^{C} +/- 0.048	0.32^{C} +/- 0.007
Cumulative Biogas/VS (ml/g)	450^{A} +/- 87	440^{A} +/- 110	42^{B} +/- 1.5	39^{B} +/- 8.7	48^{B} +/- 1.0
Cumulative CH_4/Substrate (ml/g)	11^{A} +/- 0.34	6.7^{B} +/- 1.3	0.041^{C} +/- 0.00	0.078^{C} +/- 0.017	0.10^{C} +/- 0.00
Cumulative CH_4/VS (ml/g)	320^{A} +/- 62	330^{A} +/- 69	6.6^{B} +/- 0.36	11^{B} +/- 2.8	9.3^{B} +/- 0.26
% CH_4	$70\%^{B}$ +/- 0.17%	$80\%^{A}$ +/- 0.38%	$15\%^{E}$ +/- 0.38%	$27\%^{C}$ +/- 1.6%	$20\%^{D}$ +/- 0.46%

$^{A, B, C}$ Samples with different letters indicate significantly different proportional changes in means based on one-way, between subjects ANOVA testing with subsequent Tukey HSD (p<0.05).

Biogas and methane production efficiencies (gas produced per gram of substrate or gram of VS added) and standardized methane production for BMP #1 and #2 are shown in Table 3-3 and Table 3-5. ANOVA and Tukey HSD analysis revealed significantly higher methane production per gram substrate in scraped manure (11.2 ml CH_4/g substrate) than in the separated liquid manure (6.7 ml CH_4/g substrate), which in turn produced significantly more CH_4 per gram of substrate than any other manure type in the trial. Similarly, the scraped and separated liquid manure fractions produced significantly more methane per gram of volatile solids (325.8 ml CH_4/g VS and 315.5 ml CH_4/g VS, respectively) than any other liquid manure, while differences between the other manure fractions were insignificant. Methane production was significantly greater in the separated liquid manure (79.8%) than in the scraped manure (70.4%); significantly higher in the scraped manure than the post-treatment lagoon manure (27.1%); significantly higher in the lagoon manure than the BARC digester inoculum (19.5%); and significantly greater in the inoculum than the digester effluent (15.4%).

3.3.1.2 Solids Destruction

Significant differences in solids destruction were found between manure types. Total and volatile solids destruction was significantly greater in the separated liquid portion of the manure (36.7% and 54.3%, respectively) than in all other fractions except the scraped manure (20.3% and 25.5%) and inoculum (9.5% TS).

3.3.1.3 Alkalinity and pH

Neither alkalinity nor pH changed significantly during BMP #1.

3.3.1.4 Nitrogen – TKN, NH_4^+-N, and C/N Ratio

For BMP #1, the TKN in the digester effluent was significantly greater from its pre-digestion TKN value (760 mg/L versus 1063 mg/L), while none of the manure fractions exhibited significantly different proportional changes in TKN. Ammonium values did not differ significantly within treatments or between manure types, although an increase was observed in the scraped and separated liquid manures. The post-treatment lagoon waste exhibited a significantly greater change in C/N (79.0% decrease) than all other waste types. The scraped, separated liquid and digester effluent fractions showed insignificant decreases.

3.3.1.5 Phosphorus – TP and orthophosphate (PO_4^{3-}-P)

There were no differences between influent and effluent values for TP or PO_4-P. All waste fractions except for the inoculum did, however, exhibit a statistically insignificant trend towards increasing values of TP and PO_4-P in the effluent.

3.3.1.6 Potassium

The 35-day BMP trial showed no significant changes in TK values from influent to effluent within treatments or between treatments for any of the waste fractions tested.

Table 3-4 - Influent and effluent values for BMP #1 (+/- SEM; n=3)

Value	Scraped Manure		Separated Liquid Manure		Digester Effluent		Post-Treatment Lagoon		Inoculum	
	In	Out	In	Out	In	Out	In	Out	In	Out
TS (mg/g)	48.6	36.9	30.5	19.3*	11.0	10.5	12.0	11.4	12.0	10.8*
	+/- 7.77	+/- 2.55	+/- 0.600	+/- 0.844	+/- 0.200	+/- 0.343	+/- 0.616	+/- 0.179	+/- 0.177	+/- 0.0841
[Avg. % Change]	-24.1%^{A,B}		-36.7%^{A}		-4.54%^{B}		-5.00%^{B}		-10.0%^{A,B}	
VS (mg/g)	38.8	25.3	21.4	9.81*	6.12	5.93	6.60	6.19	6.62	5.83*
	+/- 7.30	+/- 0.741	+/- 0.690	+/- 0.496	+/- 0.358	+/- 0.338	+/- 0.500	+/- 0.177	+/- 0.0716	+/- 0.0616
[Avg. % Change]	-34.8%^{A,B}		-54.2%^{A}		-3.10%^{B}		-6.21%^{B}		-11.9%^{B}	
pH	8.22	7.55*	7.84	7.58*	8.10	7.64*	8.41	7.58*	7.90	7.61*
	+/- 0.34	+/- 0.01	+/- 0.05	+/- 0.03	+/- 0.05	+/- 0.02	+/- 0.11	+/- 0.03	+/- 0.03	+/- 0.03
[Avg. % Change]	-78.6%		-45.0%		-65.6%		-85.1%		-48.3%	
Alkalinity (mg CaCO3/L)	6130	6590	6670	7020	5670	6160*	5230	5510*	6170	6460
	+/- 312	+/- 97.4	+/- 329	+/- 150	+/- 46.8	+/- 81.0	+/- 146	+/- 93.6	+/- 167	+/- 27.0
[Avg. % Change]	+7.50%		+5.25%		+8.64%		+5.35%		+4.70%	
TKN (mg/L)	1830	1950	1420	2010	760	1060*	440	650	1260	1060
	+/- 439	+/- 161	+/- 387	+/- 55	+/- 77	+/- 12	+/- 90	+/- 5	+/- 80	+/- 18
[Avg. % Change]	+6.56%		+41.5%		+39.5%		+47.7%		-15.7%	
NH_4^+-N (mg/L)	347	965	585	1000	678	611	317	309	720	642
	+/- 218	+/- 69.5	+/- 154	+/- 229	+/- 8.73	+/- 18.5	+/- 30.2	+/- 9.62	+/- 24.2	+/- 13.1
[Avg. % Change]	+178%		+70.9%		-9.88%		-2.52%		-10.8%	
TP (mg/L)	15.8	260	216	313	110	139	83.1	96.6	222	155
	+/- 87.9	+/- 67.1	+/- 92.6	+/- 17.8	+/- 23.0	+/- 6.66	+/- 17.4	+/- 6.62	+/- 37.3	+/- 8.99
[Avg. % Change]	+1550%		+44.9%		+26.4%		+16.2%		-30.2%	
PO_4^{3-}-P (mg/L)	79.0	274	165	254	125	127	98.6	102	131	130
	+/- 153	+/- 10.8	+/- 66.8	+/- 32.0	+/- 2.86	+/- 1.78	+/- 3.04	+/- 1.87	+/- 4.24	+/- 2.55
[Avg. % Change]	+247%		+53.9%		+1.60%		+3.45%		-0.763%	
TK (mg/L)	1722	1818	1685	1905	1546	1494	1718	1715	1649	1610
[Avg. % Change]	+5.575%		+13.06%		-3.364%		-0.1746%		-2.365%	
C:N Ratio	9.8	7.0*	7.5	6.4*	7.2	4.6*	6.5	1.3*	6.0	6.8
	+/- 0.54	+/- 0.41	+/- 0.17	+/- 0.15	+/- 0.10	+/- 0.67	+/- 0.62	+/- 0.44	+/- 0.32	+/- 0.59
[Avg. % Change]	-29%^{B}		-15%^{BC}		-36%^{B}		-80%^{A}		+13%^{C}	

* Denotes significant differences between influent and effluent values for the given manure type based on Student's T-test ($p<0.05$).

$^{A, B, C}$ Samples with different letters indicate significantly different proportional changes in means based on one-way, between subjects ANOVA testing with subsequent Tukey HSD ($p<0.05$).

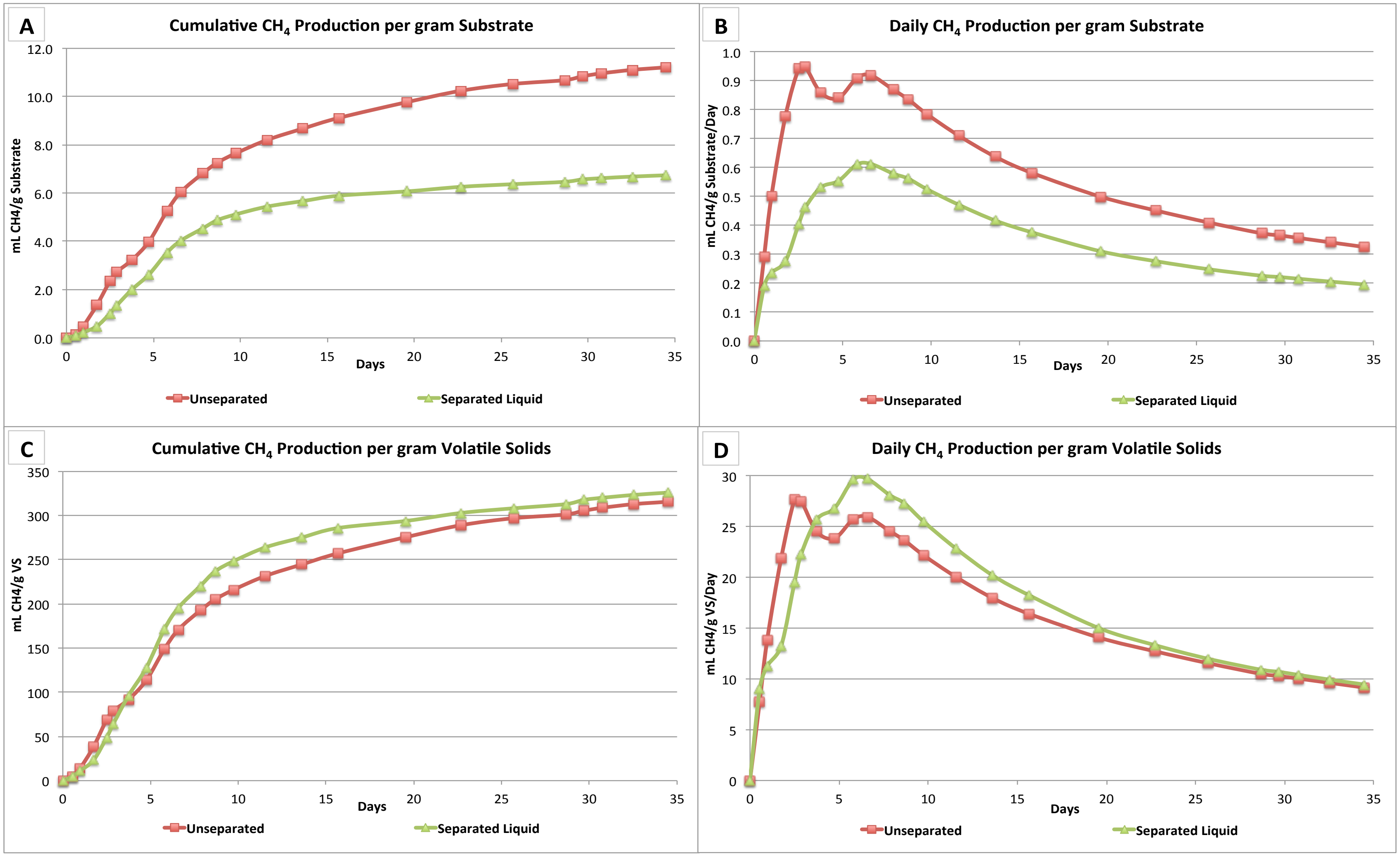


Figure 3-1 - Methane production in the high-producing manure fractions in BMP #1

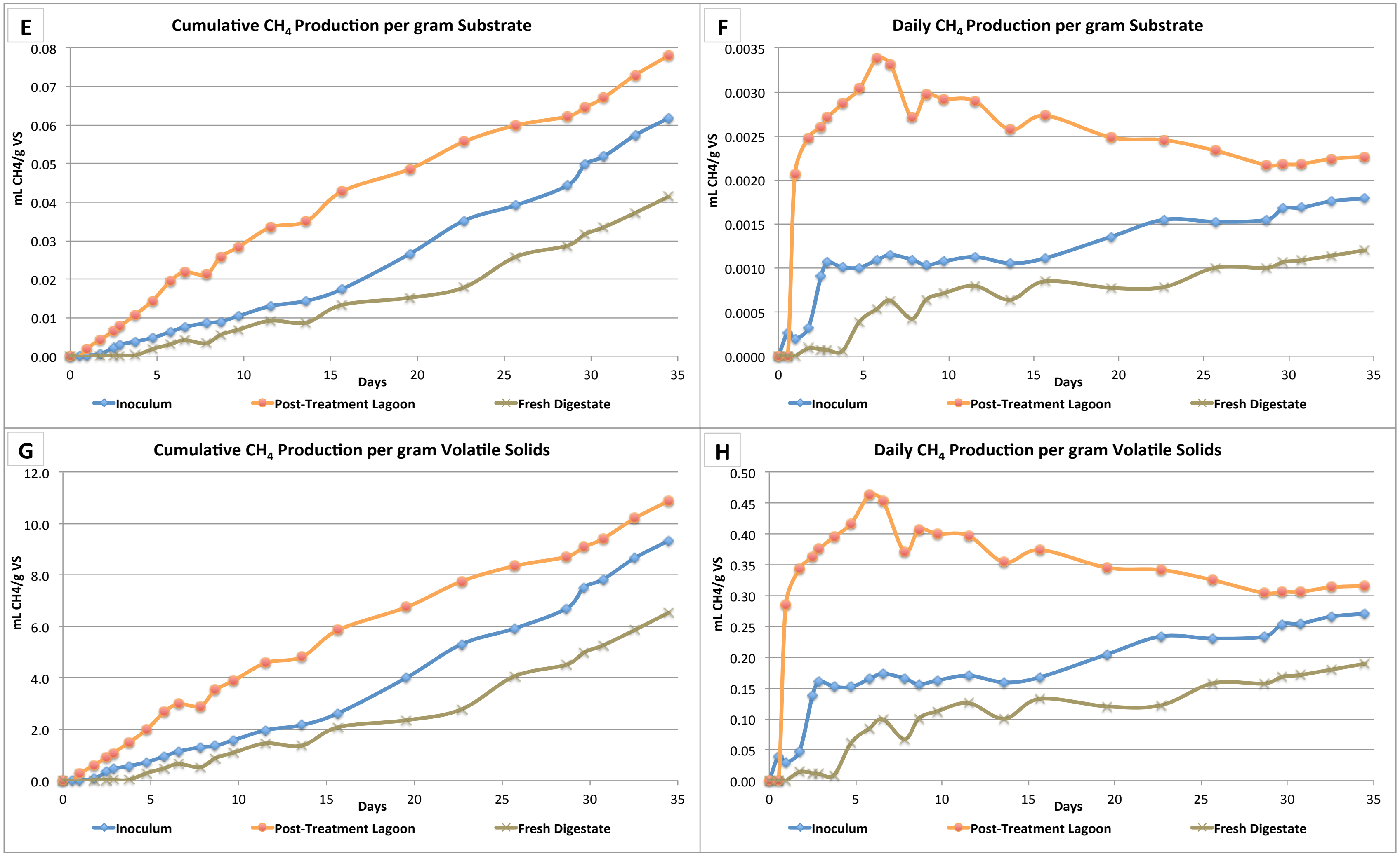


Figure 3-2 - Methane production in the low-producing fractions of manure in BMP #1

3.3.2 BMP #2: 61-day High-Solids Manure BMP Trials

The pre- and post-digestion characteristics of the high-solids fractions of the BARC dairy waste stream are shown in Table 3-6. Significant differences were found in terms of biogas production, methane production, methane content in the biogas, TS, VS, C/N, and pH.

3.3.2.1 Gas Production and Response to Inoculum

Biogas and methane production efficiencies (gas produced per gram of substrate or VS) and standardized methane production for BMP #1 and BMP #2 are shown in Table 3-6. Biogas and methane production exhibited a rapid initial increase after start-up, reaching a level of 22.1 ml biogas/gVS/day (0.38 ml CH_4/gVS/day) in the 20% inoculum:solids treatment. However, gas production then steadily decreased in all treatments over a period of 20-25 days before again increasing to match and surpass the original production rate (Figure 3-3). In BMP #2, there was significantly higher methane production per gram of substrate in the 33% inoculum:separated solids treatment (14.8 ml CH_4/g substrate) compared to the 20% inoculum:separated solids treatment (12.0 ml CH_4/g substrate), which was significantly greater than all other treatments in the trial, indicating a significant response to supplemental inoculum. The 33% inoculum:separated solids treatment also produced significantly more methane per gram of volatile solids (105.1 ml CH_4/g VS) than the 20% inoculum:separated solids mix (69.1 ml CH_4/g VS), which in turn produced more than the other high-solids treatments. Methane production in the biogas was significantly greater in the 33% and 20% inoculum:separated solids treatments (31.7% and 30.4%, respectively) than in any other manure types in the 61-day trial. The gas production response to supplemental inoculum in the dried solids treatments was not significantly different from the non-supplemented control.

3.3.2.2 *Solids Destruction*

Table 3-5 - Solids destruction and gas production in BMP #2 (+/- SEM; n=3)

Value	Separated Solid Manure	Separated Solid Manure - 20% Inoculum	Separated Solid Manure - 33% Inoculum	Dried Separated Solid Manure	Dried Separated Solid Manure - 20% Inoculum	Dried Separated Solid Manure - 33% Inoculum
Initial VS (mg/g)	251 +/- 3.90	189 +/- 2.73	170 +/- 2.29	542 +/- 12.0	407 +/- 7.43	347 +/- 4.87
VS Destroyed (%)	8.4% +/- 1.4%	14% +/- 4.4%	12% +/- 0.85%	3.9% +/- 4.6%	0.3% +/- 2.2%	5.9% +/- 2.7%
Cumulative Biogas/Substrate (ml/g)	15^{B} +/- 3.0	39^{A} +/- 1.4	47^{A} +/- 1.2	15^{B} +/- 0.43	14^{B} +/- 2.7	14^{B} +/- 0.62
Cumulative Biogas/VS (ml/g)	64^{C} +/- 14	230^{B} +/- 9.4	330^{A} +/- 5.1	29^{D} +/- 1.2	31^{D} +/- 6.2	35^{D} +/- 1.6
Cumulative CH_4/Substrate (ml/g)	1.8^{C} +/- 0.70	12^{B} +/- 0.79	15^{A} +/- 0.56	1.6^{C} +/- 0.10	1.1^{C} +/- 0.58	0.67^{C} +/- 0.064
Cumulative CH_4/VS (ml/g)	7.7^{C} +/- 3.2	69^{B} +/- 6.4	110^{A} +/- 2.1	3.2^{C} +/- 0.20	2.3^{C} +/- 1.2	1.6^{C} +/- 0.17
% CH_4	$11\%^{B}$ +/- 3.1%	$30\%^{A}$ +/- 1.6%	$32\%^{A}$ +/- 1.1%	$11\%^{B}$ +/- 0.39%	$6.5\%^{B}$ +/- 2.4%	$4.6\%^{B}$ +/- 0.27%

$^{A, B, C}$ Samples with different letters indicate significantly different proportional changes in means based on one-way, between subjects ANOVA testing with subsequent Tukey HSD ($p<0.05$).

In BMP #2, only the separated solids treatments showed significant reductions in TS between pre- and post-digestion, with TS reductions not differing significantly between treatments. Similarly, all separated solids treatments, as well as the 33% inoculum:dried solids treatment, showed significant decreases in VS content after digestion, with the 20% inoculum:solids treatment having significantly higher TS and VS destruction (13.7% and 14.0%, respectively) than the dried separated solids containing supplemental inoculum.

3.3.2.3 *Alkalinity and pH*

pH decreased significantly more in the 33% inoculum:dried solids treatment (36.2%) than in the 33% and 20% inoculum:separated solids treatments (10.2% and 4.8%, respectively). These differences were partially the result of soured samples: two of the samples in the 20% inoculum:dried solids treatment and three of the samples in the 33% inoculum:dried solids treatment had a final pH below 6.5. As in BMP #1, manures that exhibited sustained or increased alkalinity in the high-solids trial appeared to be loosely correlated with a healthy anaerobic digestion process, as biogas and methane production was greatest in those samples. No significant changes in alkalinity were observed between the manure fractions tested in either BMP trial.

3.3.2.4 Nitrogen – TKN, NH_4-N, and C/N

In BMP #2, there was an insignificant trend towards higher effluent TKN values, with one exception. The dried separated solid manure treatment influent TKN level was significantly greater than its effluent value (4.38 g/L versus 2.92 g/L). Ammonium values increased significantly during digestion in every treatment except for the 33% inoculum:separated solids and, although the increases did not differ significantly between treatments, a trend was observed towards greater increases in the dried solids treatments. In terms of the C/N ratio, changes tended to be most evident in those treatments with greatest solids destruction. Significantly greater declines were observed in the 33% inoculum:separated solids treatment (-25.6%) than in the uninoculated separated or dried separated solid treatments (+17.4% and +12.4%, respectively).

3.3.2.5 Phosphorus – TP and orthophosphate (PO_4^{3-}-P)

In BMP #2, there were no statistically significant differences in TP, with significant increases in PO_4-P between influent and effluent values in all the high-solids treatments except for the uninoculated separated solid manure. There were no significant differences in TP or PO_4-P between any of the high-solids treatments.

Table 3-6 - Influent and effluent values for BMP #2 (+/- SEM; n=3)

Value	Separated Solid Manure		Separated Solid Manure - 20% Inoculum		Separated Solid Manure - 33% Inoculum		Dried Separated Solid Manure		Dried Separated Solid Manure - 20% Inoculum^{b}		Dried Separated Solid Manure - 33% Inoculum^{c}	
	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out
TS (mg/g)	251.2	235.2*	202.4	174.8*	182.3	161.9*	542.1	515.5	434.9	431.6	346.5	347.4
	+/- 3.907	+/- 2.306	+/- 2.739	+/- 5.552	+/- 2.331	+/- 2.134	+/- 11.96	+/- 7.415	+/- 7.715	+/- 5.487	+/- 5.539	+/- 1.463
[Avg. % Change]	-6.369%^{ABC}		-13.64%^{A}		-11.19%^{AB}		-4.907%^{ABC}		-0.7588%^{BC}		+0.2597%^{C}	
VS (mg/g)	237.2	217.3*	188.6	162.5*	170.0	150.3*	505.9	486.0	406.6	405.5	346.5	325.9*
	+/- 4.200	+/- 2.739	+/- 2.732	+/- 5.416	+/- 2.295	+/- 2.017	+/- 13.00	+/- 4.366	+/- 7.426	+/- 4.861	+/- 4.874	+/- 1.476
[Avg. % Change]	-8.390%^{AB}		-13.84%^{A}		-11.59%^{AB}		-3.934%^{AB}		-0.2705%^{B}		-5.945%^{AB}	
pH	7.94	7.52	7.95	7.56	8.02	7.20*	8.87	7.38*	8.79	5.85*	8.74	5.57*
	+/- 0.14	+/- 0.00	+/- 0.0186	+/- 0.140	+/- 0.249	+/- 0.0897	+/- 0.0837	+/- 0.0841	+/- 0.113	+/- 0.553	+/- 0.173	+/- 0.345
[Avg. % Change]	-62.0%		-58.9%		-85.0%		-96.8%		-99.9%		-99.9%	
Alkalinity (mg CaCO3/L)	9160	7310	8200	7640	7580	7450	14200	14900	12500	11000	12200	8520*
	+/- 410	+/- 1300	+/- 130	+/- 280	+/- 210	+/- 320	+/- 760	+/- 190	+/- 510	+/- 800	+/- 480	+/- 60
[Avg. % Change]	-20.2%		-6.83%		-1.27%		+4.93%		-12.0%		-30.2%	
TKN (mg/L)	2600	2920	2500	2700	1920	2300	4380	2920*	1550	2570	3240	3310
	+/- 306	+/- 152	+/- 248	+/- 347	+/- 83.1	+/- 157	+/- 106	+/- 225	+/- 97.4	+/- 890	+/- 523	+/- 800
[Avg. % Change]	+12.3%		+8.00%		+19.8%		-33.3%		+65.8%		+2.16%	
NH_4^+-N (mg/L)	112	336*	122	263*	194	193	82.1	260*	44.1	412*	92.8	569*
	+/- 19.9	+/- 53.2	+/- 30.0	+/- 17.7	+/- 17.2	+/- 12.3	+/- 25.3	+/- 12.5	+/- 19.8	+/- 105	+/- 27.1	+/- 18
[Avg. % Change]	+200%		+116%		-0.515%		+217%		+834%		+513%	
TP (mg/L)	309	321	311	294	228	288	676	555	307	487	455	587
	+/- 36.5	+/- 17.4	+/- 32.2	+/- 34.1	+/- 10.5	+/- 19.1	+/- 43.1	+/- 31.3	+/- 2.65	+/- 95.3	+/- 49.6	+/- 110
[Avg. % Change]	+3.88%		-5.47%		+26.3%		-17.9%		+58.6%		+29.0%	
PO_4^{3-}-P (mg/L)	152	212	109	227*	124	184*	306	395*	213	386*	212	374*
	+/- 9.42	+/- 26.7	+/- 9.75	+/- 16.8	+/- 10.5	+/- 5.81	+/- 10.4	+/- 15.8	+/- 16.3	+/- 24.4	+/- 15.3	+/- 3.01
[Avg. % Change]	+39.5%		+108%		+48.4%		+29.1%		+81.2%		+76.4%	
TK (mg/L)	1695	1931	1760	1519	1604	1764	3654	4387	2914	3702	2299	3018
[Avg. % Change]	+13.92%		-13.69%		+9.975%		+20.06%		+27.04%		+31.27%	
C:N Ratio	37.1	43.3	40.2	34.1	41.4	30.7*	36.2	40.7	37.5	39.1	37.2	38.7
	+/- 2.13	+/- 0.570	+/- 1.95	+/- 1.17	+/- 3.01	+/- 1.92	+/- 0.911	+/- 2.71	+/- 1.80	+/- 2.50	+/- 0.57	+/- 1.86
[Avg. % Change]	+16.7%^{B}		-15.2%^{AB}		-25.8%^{A}		+12.4%^{B}		+4.26%^{AB}		+4.03%^{AB}	

[*] Denotes significant differences between influent and effluent values for the given manure type based on Student's T-test ($p<0.05$).

[A, B, C] Samples with different letters indicate significantly different proportional changes in means based on one-way, between subjects ANOVA testing with subsequent Tukey HSD ($p<0.05$).

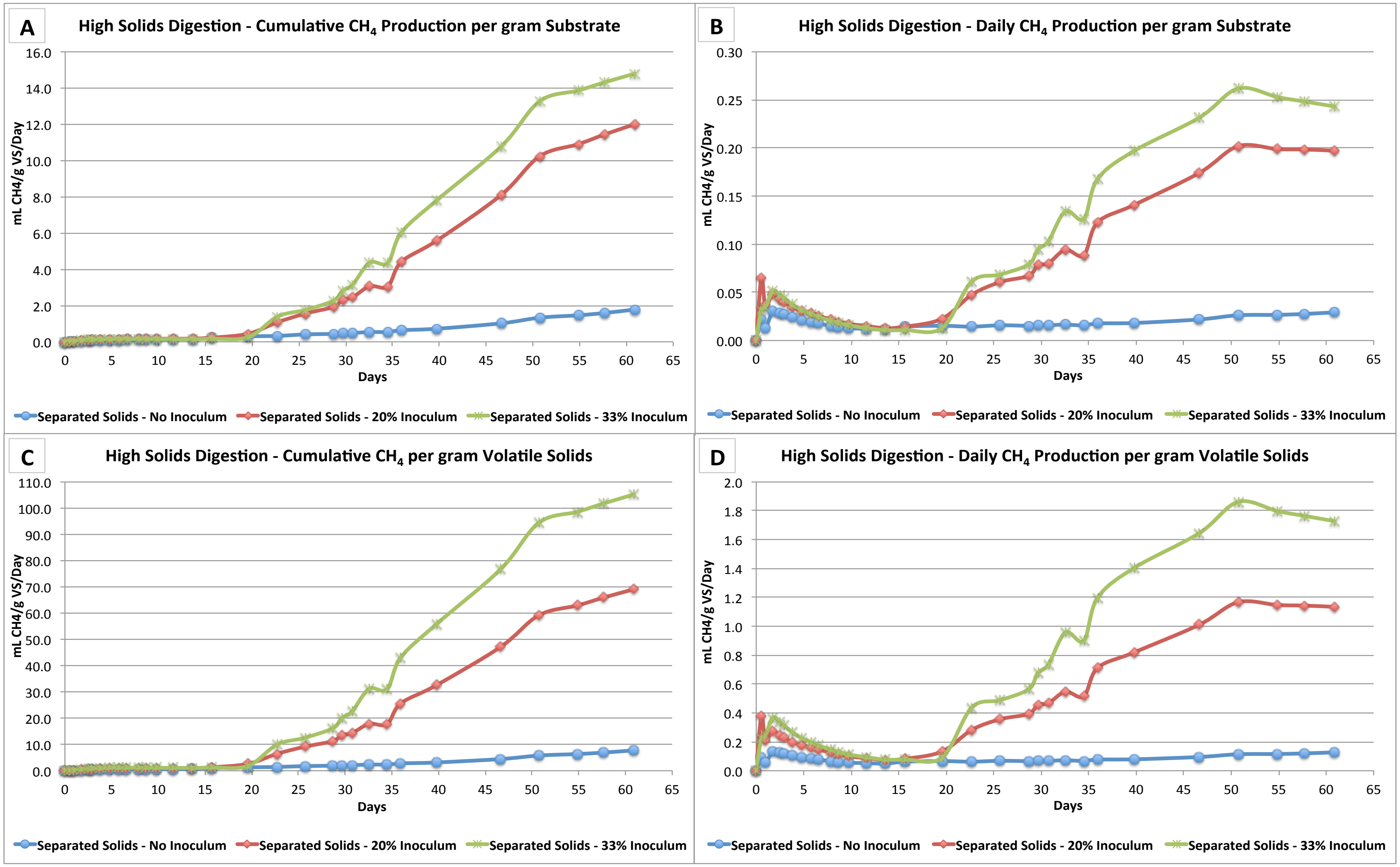


Figure 3-3 - Methane production in the high-producing manure fractions in BMP #2

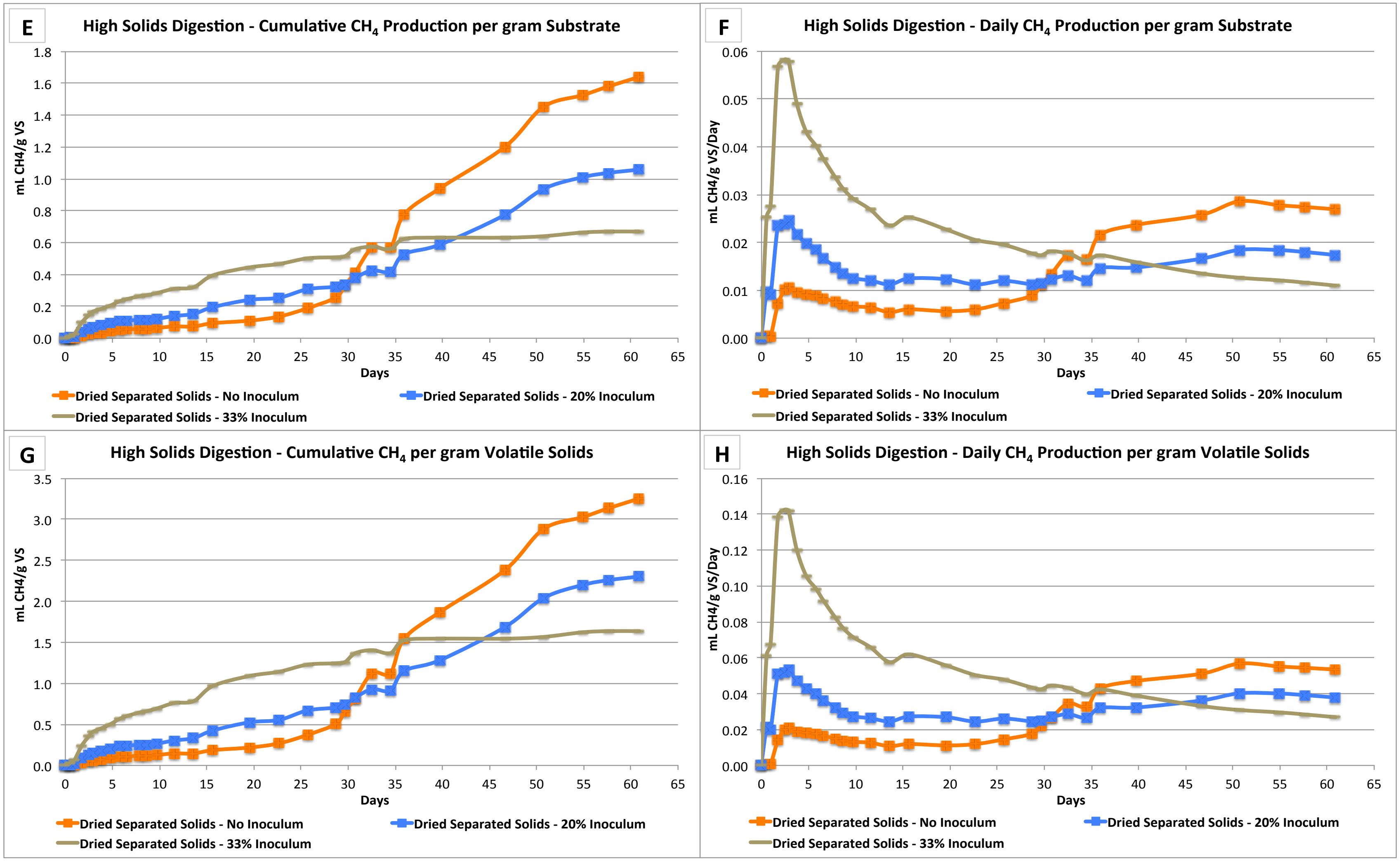


Figure 3-4 - Methane production from the low-producing manure fractions in BMP #2

3.4 Discussion

3.4.1 Gas Production as a Function of Waste Characteristics

This study found the highest biogas production per unit VS and substrate was produced from the unseparated, scraped manure and the separated liquid fraction of the BARC dairy waste. Scraped manure showed the highest rate of methane production (11 ml CH_4/g substrate), a finding most probably explained by its higher relative VS content – 48.6 mg/g versus 30.5 mg/g in the separated liquid manure. This study also found similar methane and production per unit VS added between separated liquid dairy manure (315.5 ml CH_4/g VS) and scraped manure (325.8 ml CH_4/g VS). These findings support the practice of pre-digestion solids separation, as comparable methane production and lower reactor costs may be possible without the problems and maintenance associated with recalcitrant solids accumulation in anaerobic digestion systems described by (Inglis et al., 2007; Scruton, 2007).

This study found methane production to be generally in keeping with the findings of previous studies investigating the anaerobic digestion of dairy manure. (Pain et al., 1984) reported average methane production for separated liquid manure and unseparated manure to be 347 ml CH_4/g VS and 255 ml CH_4/g VS at a 20-day retention time, respectively, with 26.5% more methane production from separated liquid manure, compared to the statistically insignificant 3.2% observed in this study). Our study also found that the residual gas production from treated manure – represented by the anaerobic digester effluent and post-treatment lagoon fractions of the manure waste stream – was not insignificant at mesophilic temperatures (6.6 ml CH_4/g VS and 11 ml CH_4/g VS, respectively). (Safley Jr. and Westerman, 1988) found that methane production from an anaerobic lagoon ranged from roughly 0.7 ml CH_4/g substrate to 5.2 ml CH_4/g substrate, with the high range representing 47% of the total digester effluent production levels observed in this study. (Rico et al., 2011) found post-digestion dairy manure to produce 15 ml CH_4/g VS to 103 ml CH_4/g VS in BMPs conducted at 35 ºC over a 60-day period, which is 25-900% more than this study's findings, although the BMP experiment ran for an addition 25 days. These findings underscore the importance of covered post-digestion storage, especially in light of the greenhouse gas-related implications of persisting methane releases.

In BMP #2, the highest-preforming manure – separated solid manure with a 33% inoculum supplement – was found to produce methane at a rate approaching only one-third of the production found in separated liquid manure in terms of VS (110 ml CH_4/g). However, in terms of pure substrate mass, separated solid dairy manure with 33% inoculum outperformed all other fractions of manure (15 ml CH_4/g substrate). This finding was tempered by the low methane concentrations (5-23%) observed in the high-solids manure treatments in our trial, a finding not supported by previous studies (Ahn et al., 2010; Hall et al., 1985; Hills, 1980; Li and Wang, 2011) (Table 3-7). The methane content of the biogas produced has serious implications for the anaerobic digestion's economic viability in situations where it will be used for generating electricity or powering engines, as the ideal methane content for biogas generators has been reported to be 60% (Constant et al., 1989). This implies the need for extensive CO_2 scrubbing to achieve viable methane content for low methane-containing gas. However, this high-solids digestion BMP trial did not employ digestate recirculation or mixing, features that were used in the (Hills, 1980), (Hall et al., 1985), and (Ahn et al., 2010) papers and that have been shown to improve high-solids digestion performance (Francois et al., 2007; Novella et al., 1997; Vavilin et al., 2003).

Table 3-7 - Mean solids destruction and gas production from high-solids dairy manure digestion studies

Study	Substrate	% TS (wet)	% VS (wet)	% Inoculum (weight)	% VS Destruction	L CH_4/g VS fed	Temp. (ºC)	Retention Time (RT)(days)	Mixing?	Leachate Recirculation?
This Study	Dairy manure	25.1	23.7	0	6.7	0.008	35	61	No	No
This Study	Dairy manure	20.2	18.9	20	14.0	0.069	35	61	No	No
This Study	Dairy manure	18.2	17.0	33	11.6	0.105	35	61	No	No
Hills, 1980	Dairy manure	19.1	16.2	8	40.8	0.179	35	100	Yes	No
Hall et al., 1985	Dairy manure & wheat straw	26.3	21.0	~50	31.2	0.135	30	70	No	Yes
Ahn et al., 2010	Dairy manure & switchgrass	15.2	14.4	~20	9.3	0.002	55	62	Yes	No
Li and Wang, 2011	Dairy manure	20.0	--	--	9.8	0.110	35	60	No	No

In addition, BMP #2 indicated a significant effect on methane production in the separated solids substrates with increasing inoculum to waste ratios (Table 3-5). This effect has been documented in other studies and may be attributed to the ability of the inoculum to more quickly stabilize the digestion process by establishing a large initial methanogenic population (Forster-Carneiro et al., 2008; Lopes et al., 2004). However, in the dry solids treatments, the inoculum response was not detected. Reduced alkalinity and pH values in the effluent indicate that this was likely the result of souring of the digester environment, as acids produced by the initial hydrolysis and acidogenesis processes may have accumulated to inhibit methanogenic activity. (Martin, 2001) proposed the reaction front theory of high-solids digestion which hypothesizes that the anaerobic digestion reaction originates from areas of active methanogenesis and moves via contact with surrounding organic substrate or by the transport of raw organic material to areas of active methanogenesis (Martin and Xue, 2003; Martin, 2001; Martin et al., 2003a, 2003b). The low bulk density of the dry solids treatments, coupled with the lack of compaction and mixing, may have led to the inhibition of progress to Martin's proposed reaction front, thereby resulting in an overly acidic digestion environment and an associated reduction in methane production. However, Martin's theory may not completely explain the low gas production from the uninoculated dried solids treatment, in which the final pH was found to be slightly above neutral. A potential explanation may be found in the low initial moisture content of the sample (45.8%), which (Lay et al., 1997) has shown falls below the moisture threshold limits (56.6%) for microbial survival in several common organic wastes in high-solids digestion.

In both BMP trial studies, a trend towards neutral or increasing alkalinity was observed in treatments producing relatively large volumes of biogas. The lack of significant change in alkalinity in many of the digested samples is consistent with other findings (Ahn et al., 2010; Li and Wang, 2011) and may result from the natural biochemical processes that occur within the anaerobic digestion process. As proteins and amino acids are broken down during methanogenesis, amino groups are cleaved and freed to interact with free CO_2 and water in solution to form ammonium carbonate, a source of alkalinity (Gerardi, 2003):

$$NH_3 + CO_2 + H_2O \rightarrow NH_4HCO_3$$

Ammonium carbonate may then act to neutralize acidity via the following:

$$NH_4HCO_3 + R\text{-}COOH \rightarrow R\text{-}COONH_4 + H^- + HCO_3^-$$

Because this process is initiated by the activity of methanogenic bacteria, stable or increasing alkalinity may be viewed as an indicator of a healthy anaerobic digestion system (Kim et al., 2002).

In general, the methane generation rates documented by the liquid and high-solids dairy manure BMP trials support experience from scientific research and the anaerobic digestion industry, which has found digestion to be suitable for raw, separated or unseparated dairy manure in terms of energy production potential. However, there is a lack of consensus on when and if additional efforts at methane capture from treated manure are merited due to the high variability in production potential. Rico et al. (2011) concluded that post-treatment lagoons should be covered due to appreciable biogas and methane production, while Safley and Westerman (1988) argue the opposite due to inconsistent production and inferior quality, i.e. low methane content. Our study found that 0.04 – 0.08 ml CH_4/g substrate (6.7 – 11 ml CH_4/g VS) could be produced from the effluent of the digested separated liquid in addition to the 6.7 ml CH_4/g substrate (330 ml CH_4/g VS) already produced.

3.4.2 The Efficacy of Solids Treatment in Digestion

Of the measurable components of the dairy manure waste stream with significant potential impacts on nutrient management and the environment, only the total solids, volatile solids, and C/N ratio were significantly reduced during anaerobic digestion in any fraction of the BARC dairy manure. In the 35-day liquid manure BMP trial, the scraped and separated liquid manures exhibited the two largest decreases in total and volatile solids during digestion, although the difference in solids concentrations between influent and effluent in the scraped manure was not statistically significant. Solids reduction is directly tied to biogas production, and biogas production in these two samples was significantly higher than in any other fraction of the waste. Therefore, the anomaly in solids destruction in the scraped manure is likely due to the large variances exhibited between samples and low replication, as numerous other studies have reported similar reductions between 3-16% for VS and up to 26% TS from scraped manure (Hart, 1963; Martin, 2005; Pain et al., 1984). In the case of the digester effluent and post-treatment lagoon manures, the low levels of solids destruction observed is likely due to relatively low initial solids content and VS/TS ratios, suggesting that additional treatment via anaerobic digestion may have little effect on the further reduction of total and volatile solids for these fractions of the BARC dairy waste stream.

Although exhibiting significant differences between influent and effluent TS & VS concentrations and C/N ratios, the high-solids manure treatments showed relatively poor solids treatment despite their 61-day retention time (0.3%-14% TS destruction). This is likely the result of the inhibition processes discussed in section 1.4.1, including souring and low moisture content. Table 3-7 provides information on volatile solids destruction in previous high-solids digestion studies undertaken on dairy manure and shows a high level of reported variability in solids treatment. This variability underscores both the promise and potential drawbacks of high-solids digestion as a viable mechanism for dairy manure processing, as high-levels of solids treatment are possible but require more attentive management to ensure treatment uniformity and consistency. Even with 33% inoculum to substrate ratios, the C/N ratios never fell below 30:1 in the treated manure. As composting is accomplished most effectively at C/N ratios of 25:1 to 40:1, treated high-solids manure appears ideal for further processing into a finished compost product if combined with bulking agents to allow aeration.

In general, reductions in volatile solids as the result of the mesophilic anaerobic digestion of liquid dairy manure have been reported to average between 50-55% for 30-day solids retention times (SRTs) and between 55-60% for 60-day SRTs, depending on the solids loading rate (Burke, 2001). In BMP studies, hydraulic retention times (HRTs) are equal to SRTs, and this study found volatile solids destruction rates to fall short of reported averages in all but the separated liquid manure (54.3% reduction at 35 days HRT/SRT). In general, volatile solids destruction rates will never exceed 65% in anaerobic digestion processes due to the inability of bacteria to degrade the lignified fraction of a waste's total volatile solids (Ciborowski, 2001). For the farmer, this means that although substantially reduced, wastes solids management is a requirement of any anaerobic digestion process. Solids separation, occasional digester cleanouts, and effluent slurries containing fine, suspended solids are realities that may affect any manure and nutrient management plan (Burke, 2001).

3.4.3 Nutrient Treatment and Transformations from Anaerobic Digestion

Although changes in nutrient speciation were observed during each of the dairy manure BMP trials, overall nutrient levels were largely conserved. In the liquid dairy manure trial, total kjeldahl nitrogen values changed significantly in only one sample – the re-digested digester effluent – as a result of the digestion process. Although they do not explain the reason, (Schievano et al., 2011) have documented similar findings, and it could be that it is the result of the production of relatively large quantities of water vapor in the biogas which, given simultaneously low levels of ammonia production, might serve to decrease volume and increase nutrient concentrations. Stronger trends towards higher levels of ammonium and orthophosphate were observed in the digested liquid manure treatments with greatest solids destruction and biogas production, as would be expected based on the nutrient transformations which have been established to take place during anaerobic digestion (Field et al., 1984; Massé et al., 2007; Schievano et al., 2011). Potassium levels, albeit based on non-replicated analysis, seemed to remain generally unchanged, which is also supported by the literature (Massé et al., 2007; Schievano et al., 2011).

The high-solids BMP trial exhibited very similar results in terms of nutrient retention and transformation. Again, only one treatment – the 0% inoculum:dried solids – showed significantly different TKN values after digestion. The decrease may be the result of gaseous ammonia loss during the digestion process. Unlike the other dry solids treatments, the pH did not fall below 7.0 as a result of digestion and there was very little moisture for which the ammonia could be absorbed into solution – conditions more suitable to N-loss from volatilization (Meisinger and Jokela, 2000). Nearly all of the high-solids treatments displayed significantly higher levels of water-soluble ammonium and orthophosphate after digestion, perhaps due to their lower influent levels relative to liquid dairy manure, or perhaps due to extensive hydrolysis, which has been cited in previous studies (Abouelenien et al., 2009).

TKN to TP ratios in the digester manures with efficient biogas production ranged from 6.4/1 in the separated liquid manure to 9.2/1 in the 20% inoculum:wet solids, which resembles figures for digested swine manure reported by (Massé et al., 2007) and approaches and surpasses the 7.5/1, which is the N/P ratio required by corn. TKN/P/K ratios ranged from 6.4/1/6.1 in the separated liquid fraction to 9.2/1/5.2 in the 20% inoculum:wet manure solid fraction of the dairy manure. These ratios are slightly higher than values reported by (Voca et al., 2005) in digestion studies of chicken and pig manures, and exceed N/P/K uptake requirements of crops such as wheat (1.2/1/1.5) and pasture grass (2.4/1/1.4). In general, the prevalent form of nitrogen in digestate – ammonium-N – is cited as being more plant available than other forms of nitrogen

(Hamilton and Heemstra, 2012), although orthophosphate and potassium have been documented as less plant-extractable, potentially due to increased sorption to manure and soil particles after digestion (Field et al., 1984). Taken together, these characteristics seem to make anaerobic digestate from dairy manure a fairly good fertilizer capable of supplying the macro-nutrient needs of numerous plants and crops, and occasionally doing so in excess.

3.4.4 Implications of Anaerobic Digester Effluent Characteristics on Nutrient Management Plans

For dairies with or without arable land, nutrient management plans may entail the documentation of all on-farm nutrient flows, risk assessments for runoff, erosion, and leaching, and the application of best management practices that fulfill NRCS requirements (Rasmussen and Adams, 2004). For farms with crop land, such requirements may include, but are not limited to: 1) a full accounting of on-farm nutrients flows; 2) justifying fertilizer application rates based on expected yields, soils, climate, cropping system, and fertilizer characterization; 3) avoiding nutrient application near water conveyance features (ditches, gullies, surface inlets, streams) or features directly exposed to groundwater (wells, sinkholes, sandy soils); 4) limiting nutrient loss to water bodies and groundwater via controlled and conservative application techniques, attention to soil infiltration rates, and the implementation of soil conservation measures; 5) adjusting the timing of nutrient application to maximize plant uptake and minimize volatilization, leaching and runoff resulting from climatic conditions and irrigation; and 6) regularly testing and analyzing soil and plant nutrient levels (NRCS, 2006).

The lower levels of solids and higher levels of soluble nutrients characteristic of anaerobic digestion effluent may facilitate nutrient management in a number of ways. (Ghafoori and Flynn, 2006) detail the low total solids and viscosity of AD digestate relative to undigested manure, which enable more efficient and longer-distance pumping – allowing farmers to spray irrigate when conditions allow. In addition, these characteristics facilitate nutrient injection during field application, as well, which has been proven to minimize ammonia volatilization and reduce phosphorus runoff (King et al., 2012; Misselbrook et al., 2002; Rotz et al., 2011; Thompson et al., 1987). The reduction in the organic fraction of waste during digestion translates to lower levels of particulate matter susceptible to runoff after application, and the increased proportions of mineralized species (e.g. ammonium and orthophosphate) that are more immediately available for plant uptake and which enable more accurate calculation of application rates and eventual assimilation into crops (Eghball et al., 2002). On a negative note, the increased level of ammonium in digestate may pose storage problems in terms of nutrient management, as prolonged open-air retention or land application may lead to increased loss via volatilization in digestate relative to raw manure (Balsari et al., 2010; Ni et al., 2012).

3.4.5 Secondary Treatment Options Provided by Anaerobic Digestion

For dairies which are specifically nutrient limited in their field application of manures or simply unable to field apply their anaerobic digester effluent, the unique characteristics of the waste may provide a number of post-digestion treatment options not possible with raw manure. For example, the breakdown of organically-bound nutrients, especially nitrogen and phosphorus, into inorganic and predominantly soluble forms provides the possibility for efficient nutrient recovery and stabilization relative to raw manures. Several studies suggest the possibility of raising digestate pH to precipitate out orthophosphate and ammonium as struvite, thereby providing a potential fertilizer product in the resulting crystallized compound (Jaffer et al., 2002; Münch and Barr, 2001; Schäfer et al., 2006). (Jaffer et al., 2002; Münch and Barr, 2001; Shu et al., 2006) documented the possibility of high-rate (95%+), cost-effective phosphorus removal from digestate via the addition of magnesium hydroxide or a combination of sodium hydroxide and magnesium. Conversely, for farmers facing phosphorus-limited slurry applications, acidification of the digestate reduces the proportion of soluble nitrogen in ammonia form, thereby alleviating N-loss due to ammonia volatilization and retaining nitrogen for application as plant-available ammonium (Stevens et al., 1992).

(Álvarez et al., 2008) found anaerobic digestion to be a particularly effective pre-treatment process for wastes designed to be secondarily treated by constructed wetlands. They found that the solids reductions provided by anaerobic digestion, especially the reductions in total suspended solids, allowed for increased operational lifetimes of constructed wetlands and decreased surface area requirements. The NRCS established the Wetlands Reserve Program as part of the 2008 Farm Bill that provides financial assistance to create wetlands from currently farmed wetlands, prior converted cropland, and farmed wetland pasture, effectively providing incentives to consider wetlands as a form of secondary treatment (110th U.S. Congress, 2008). (Luederitz et al., 2001), however, cite the poor capacity of constructed wetlands to remove ammonium-N, and it is likely that only select digester waste streams would prove appropriate for this form of secondary treatment.

A number of other secondary treatment options remove ammonium-N and inorganic phosphorus quite efficiently. (Cheng et al., 2002; Xu and Shen, 2011) have shown that biomass generation in the form of duckweed is an effective form of nutrient removal when treating diluted liquid digester effluent, reducing NH_4^+-N by over 85%, TN by up to 35%, and orthophosphate by nearly 20% under ideal conditions. The resulting duckweed plant mass is recognized as a viable animal food source – it contains a relatively large proportion of high-quality protein (15-40% on a dry weight basis) and is easily digestible due to its lack of lignin – and it may represent a marketable product or an opportunity for cost-savings for farmers (Bhanthumnavin and Mcgarry, 1971; Cheng et al., 2002). In addition, algae as biomass have also been explored as value-added products from secondary treatment processes operating on digestate. (Kebede-Westhead et al., 2003) showed algae grown on algal turf scrubbers to remove TN and TP from diluted dairy manure digestate at the rate of 1.3g/m^2/day and .21g/m^2/day, respectively, although (Pizarro et al., 2006) found the costs to be prohibitively expensive for farmers barring financial assistance or a ready market for the dried algal product. Both studies, however, cite the potential of algae as part of an effective secondary treatment process for digester effluent.

For the high-solids waste resulting from high-solids anaerobic digestion, composting has proven to be an effective secondary treatment option. (Kayhanian and Tchobanoglous, 1993) found that high-solids digestion followed by composting of municipal solid waste reduced C/N ratios from to ~37/1 in the initial organic waste stream to ~25/1 in the finished product, while reducing biodegradable volatile solids content below measurable levels and overall volume to 57% of its initial value.

3.5 Conclusions

This study found that gas production and nutrient transformations resulting from the anaerobic digestion of each distinguishable fraction of the BARC dairy manure waste stream provided the potential for environmental and economic gains if combined with careful refinement of manure management practices. Methane production and solids destruction was highest in the scraped and separated liquid dairy manure, whereas treatment efficiencies in the separated-solid dairy manure processed via high-solids digestion were markedly lower, even at extended retention times. Increased inoculum supplementation in the high-solids digestion trial led to a statistically significant increase in methane production in raw, separated solid dairy manure, although no effect was observed in dried separated solids. Interestingly, this study showed methane production per unit mass of high-solids, separated solid manure substrate to be comparable to low-solids, scraped and separated liquid manure, and the high methane production found by other studies suggests the possibility for research into split-stream processing of dairy manure.

Total nitrogen, phosphorus, and potassium levels were not shown to change significantly as a result of digestion, but significant increases in ammonium and orthophosphate were observed in high-solids manure fractions. In general, the findings were substantiated by numerous other studies on dairy manure and various other substrates (Martin, 2005, 2003; Schievano et al., 2011), and can be applied as general rules when considering the treatment characteristics of anaerobic digestion digestate. These characteristics may also facilitate the use of digester effluent as a fertilizer on farms, and can provide for a number of secondary treatment and/or value-added product production options ranging from wetland treatment to biomass generation. Each of these alternatives has the capacity to facilitate nutrient management and diminish the environmental repercussions of the concentrated waste streams associated with dairy facilities operating anaerobic digesters.

4 CONCLUSION

An accurate assessment of environmental contributions and impacts resulting from the implementation of anaerobic digestion systems is a key component of the technology's successful future growth in the United States and abroad. Although the challenges facing the industry are substantial, by applying environmental accounting tools to digestion projects and continuing to fine-tune the approach to waste treatment, both pre- and post-digestion, the anaerobic digestion community has the opportunity to continue its growth in an environmentally sustainable and progressive manner.

4.1 Future Research Needs

Judged on energy content alone, the successful exploitation of the residual value of organic waste is an operation providing slim net returns. The ratio of gross annual capital and operational costs to annual returns frequently pushes payback periods for stakeholders considering anaerobic digestion beyond the realm of feasibility. Through the conclusions of its emergy analysis, this research indicates that the production and use of multiple products from anaerobic digesters is environmentally advantageous. It is also likely that it increases its economic viability. Although it's true that each value-added product requires additional knowledge, labor and capital, many of the nutrients associated with the waste streams treated during anaerobic digestion are becoming more and more valuable due to ever-increasing exploitation and the growing scarcity that results. Phosphorus, in particular, is frequently cited as a commodity facing an impending and permanent shortage based on current trends of consumption and extraction. The future of anaerobic digestion, therefore, lies not only in energy production, but also in the ability to conserve and efficiently use these nutrient resources. Cost-effective, environmentally sustainable and ecologically based solutions to issues such as post-treatment nitrogen volatilization or sulfur and carbon dioxide loss in biogas should be more thoroughly explored.

In addition, this research suggests the potential for fractionated anaerobic digestion of dairy manure. The ability to independently digest the liquid and solid fractions of dairy manure with methane production comparable to or greater than that of unseparated manure provides the possibility for the generation of additional revenue from energy recovery and the creation of value-added products such as compost. High-solids digestion residue has been documented as a potentially promising composting substrate, although careful attention to aeration and bulking agents is required (Drennan, 2011; Drennan and DiStefano, 2010). While many farmers currently compost their separated solids and derive revenue from the finished product, there are currently no documented incidences of farms operating high-solids digesters from separated manures. The integration of high-solids digestion into the front end of the separated solids composting process might provide an additional stream of revenue or cost-savings to the farmer, especially if undertaken as a co-digestion system in which, in the current market, tipping fees from supplemental organic waste could be collected. The economic feasibility and potential environmental benefits are likely to be very dependent upon climate, scale, substrate, and guaranteed tipping contracts, however, and additional research would be needed to assess the viability of such a fractionated system.

While reviewing the literature on emergy analyses and life-cycle assessments of anaerobic digesters, it became apparent that the number of studies investigating these systems was disproportional to the number of operating digesters. Especially in light of the large number of anaerobic digesters being constructed in Europe, the size of the potential market in the U.S., and the disparity in infrastructure costs required by these systems and digesters in warmer climates, more research is needed into the net environmental benefit that they provide. There are very few settings in which turn-key, identically replicable digestion systems can be installed – waste streams and the facilities that produce them are too diverse, and they must accommodate varying climatological conditions. As a result, what may prove environmentally appropriate in one setting may be decidedly inappropriate in another, and only through the compilation of numerous, carefully conducted studies will recommendations for or against the implementation of digesters operating in varying conditions emerge. Criteria and methodologies for conducting these studies should be jointly agreed upon by organizations overseeing and advancing anaerobic digestion (AgSTAR and the American Biogas Council in the United States, the International Energy Agency (IEA) in Europe and Asia, and the Chinese and Indian governments), and data should be publically compiled so that it is available to public and private interests, alike. These measures will help to encourage a resource-focused, environmentally conscientious approach to future anaerobic digestion planning and design.

APPENDIX A: EMERGY CALCULATIONS

Haitian Human Waste Generation Process

R1 Solar radiation

Solar incidence/m2/year x footprint of digesters x conversion factor to J x transformity of sunlight

Normal solar radiation for Cange, Haiti	5.15	kWh/m2/year	Atmospheric Science Data Center, 2011
Area of hospital complex	4.38E+04	m2	
Conversion	3.60E+06	J/kWh	
Solar transformity of sunlight	1.00E+00	sej/J	By definition
Total sunlight energycontribution	8.12E+11	J/year	
Total Emergy of solar radiation	8.12E+11	sej/year	

R2/P2 Food

Per capita calorie intake/day * # people contributing * days per year * % (non)/renewable * solar transformity of Haitian diet

Total per capita daily calorie intake in Haiti	1979	kcal/person/day	UNFAO, 2012
Energy conversion	4.18E+03	J/kcal	
Number of people	340	persons	Lansing, 2011
Days per year	365	days/year	
Renweable Component	25.6%		This study
Transformity of Haitian diet	5.38E+05	sej/J	This study
Total renewable energy in Haitian diet	2.63E+11	J/year	
Total non-renewable energy in Haitian diet	7.65E+11	J/year	
Total renewable emergy consumed	1.42E+17	sej/year	
Total non-renewable emergy consumed	4.11E+17	sej/year	

R3 Groundwater

[(Per capita water consumption/day * # people contributing * days per year) + (water used for construction / lifetime of latrine)] * specific emergy of groundwater

Avg. Drinking water consumption	2560	g/person/day	Institute of Medicine, 2005
Number of people	340	persons	Lansing, 2011
Days per year	365	days/year	
Water use for construction	3.84E+06	g	Our estimate
Lifetime of latrine	40	years	Our estimate
Specific emergy of groundwater	1.14E+06	sej/g	Buenfil, 2001
Total quantity water consumed	3.18E+08	g/year	
Total emergy consumed	3.62E+14	sej/year	

R4/P3 Labor

Labor contributions to cooking/day * energy in labor * days per year * % (non)/renewable * solar transformity of labor

Total labor inputs	144	hr/day	Our estimates
Work done	3.45E+05	J/hr	Derived from UNFAO, 2012
Days per year	365	days/year	
Percentage renewable	25.6%		This study
Transformity of Labor	1.00E+07	sej/J	(Odum 1996) corrected by factor of 1.68 (Odum et al., 2000)
Total renewable labor inputs	4.64E+09	J/year	
Total non-renewable labor inputs	1.35E+10	J/year	
Total renewable emergy	4.64E+16	sej/J	
Total non-renewable emergy	1.35E+17	sej/J	

R5/P4 Concrete (latrine)

Quantity concrete * % (non)/renewable * specific emergy of concrete / lifetime of latrine

Quantity pre-mix concrete	4.10E+07	g	This study
Renewable component	2.7%		Derived from Haukoos (1995) and Campbell & Ohrt (2009)
Lifetime of latrine	40	years	Our estimate
Specific emergy of pre-mixed concrete	6.93E+08	sej/g	Haukoos, 1995
Total renewable concrete inputs	2.77E+04	g/year	
Total non-renewable concrete inputs	9.97E+05	g/year	
Total renewable emergy	1.92E+13	sej/year	
Total non-renewable emergy	6.91E+14	sej/year	

R6/P5 CMUs (Concrete Masonry Units - latrine)

Mass CMUs * % (non)/renewable * specific emergy of CMUs / lifetime of latrine

Mass CMUs	2.27E+07	g	This study
Renewable component	4.3%		Derived from Haukoos (1995) and Campbell & Ohrt (2009)
Lifetime of latrine	40	years	Our estimate
Specific emergy of CMUs	7.58E+08	sej/g	Haukoos, 1995
Total renewable CMU inputs	2.44E+04	g/year	
Total non-renewable CMU inputs	5.43E+05	g/year	
Total renewable emergy	1.85E+13	sej/year	
Total non-renewable emergy	4.11E+14	sej/year	

R7/P6 Rebar (latrine)

Quantity rebar * % (non)/renewable * specific emergy of steel / lifetime of latrine

Quantity rebar	9.09E+06	g	This study
Renewable component	4.2%		Derived from Haukoos (1995) and Campbell & Ohrt (
Lifetime of latrine	40	years	Our estimate
Specific emergy of rebar	2.77E+09	sej/g	Haukoos, 1995
Total renewable rebar inputs	9.54E+03	g/year	
Total non-renewable rebar inputs	2.18E+05	g/year	
Total renewable emergy	2.64E+13	sej/year	
Total non-renewable emergy	6.03E+14	sej/year	

R8/P7 Mortar (latrine)

Quantity mortar * % (non)/renewable * specific emergy of mortar / lifetime of latrine

Quantity mortar	2.72E+06	g	This study
Renewable component	2.7%		Assumed from concrete
Lifetime of latrine	40	years	Our estimate
Specific emergy of mortar	3.31E+09	sej/g	Pulselli et al., 2007
Total renewable mortar inputs	1.84E+03	g/year	
Total non-renewable mortar inputs	6.62E+04	g/year	
Total renewable emergy	6.08E+12	sej/year	
Total non-renewable emergy	2.19E+14	sej/year	

P1 Propane

Quantity propane used for cooking * energy content of propane * transformity of propare

Quantity propane	2268	kg/month	Lansing, 2011
Metric converion	1.00E+03	g/kg	
Energy content per unit gas	5.03E+04	J/g	
Months per year	12	months/year	
Transformity of propane	4.35E+04	sej/J	Bastianoni et al., 2009.
Total energy propane consumed	1.37E+12	J/year	
Total emergy consumed	5.96E+16	J/year	

P8 PVC (latrine)

Quantity of PVC * specific emergy of propane / lifetime of latrine

Quantity PVC	3.37E+05	g	This study
Lifetime of latrine	40	years	Our estimate
Specific emergy of PVC	9.86E+09	sej/g	Pulselli et al., 2007
Total PVC	8.43E+03	g/year	
Total non-renewable emergy	8.31E+13	sej/year	

Y1 Feces

Haiti per capita feces	151	kg feces/day	Our calculations; Polprasert (2007)
Metric conversion	1000	g/kg	Lansing, 2011
Days per year	3.65E+02	days/year	
Total feces production	5.52E+07	g feces/year	

Y2 Urine

Haiti per capita urine	291	L urine/day	Lansing, 2011
Density of urine	1200	g/L	Polprasert, 2007; Klatt, 2011
Days per year	3.65E+02	days/year	
Total urine production	1.27E+08	g urine/year	

Maryland Dairy Waste Generation Process

R1 **Solar Radiation** — **Solar insolation * footprint of open-air facility * solar transformity of sunlight**

Normal solar radiation for Maryland	3.84E+00	kWh/m2/year	Atmospheric Science Data Center, 2011
Footprint of dairy barn & milking parlor	1.72E+03	m2	
Conversion	3.60E+06	J/kWh	
Solar transformity of sunlight	1.00E+00	sej/J	By definintion
Total sunlight energycontribution	2.38E+10	J	
Total Emergy of solar radiation	2.38E+10	sej	

R2/P2 **Labor** — **Quantity of labor * work * % (non)/renewable * solar transformity of labor**

Quantity	2.45E+05	hours/year	Our estimate
Work done	6.43E+05	J/hr	Derived from UNFAO, 2012
Renewable Component	4.9%		Taken from %R for U.S. (Campbell & Orht, 2009)
Solar transformity of Labor	1.00E+07	sej/J	(Odum 1996) corrected by factor of 1.68 (Odum et al., 2000)
Total Renewable Work	7.73E+09	J/year	
Total Non-Renewable Work	1.50E+11	J/year	
Total renewable emergy	3.79E+15	sej/year	
Total non-renewable emergy	1.43E+18	sej/year	

R3/P4 **Wood Chip Bedding** — **Quantity of bedding * density of wood chips * days/year * % (non)/renewable * specific emergy of wood chips**

Quantity of bedding	3.44	me/day	Our estimate
Density of bulk wood chips	1.90E+05	g/m3	Reed, 2009
Days per year	365	days/year	
Percentage renewable	22.5%		Franzese et al., 2009
Specific emergy	3.17E+08	sej/g	Franzese et al., 2009
Total mass renewable	1.56E+07	g/year	
Total mass non-renewable	5.37E+07	g/year	
Total emergy renewable	4.95E+15	sej/year	
Total emergy non-renewable	1.70E+16	sej/year	

R4/P5 **Concrete (barn footers & pad)** — **Quantity/year * % (non)/renewable * specific emergy of concrete**

Quantity	5.36E+07	g/year	Our estimate
Percentage renewable	1.0%		Derived from Haukoos (1995) and Campbell & Ohrt (2009)
Specific emergy	1.20E+09	sej/g	Haukoos, 1995
Total renewable quantity concrete	5.36E+05	g/year	
Total non-renewable quantity concrete	5.31E+07	g/year	
Total renewable emergy	6.44E+14	sej/year	
Total non-renewable emergy	6.37E+16	sej/year	

R5/P8 Galvanized Steel (barn structure)

Quantity/year * % (non)/renewable * specific emergy of steel

Quantity	1.90E+06	g/year	Our estimate
Percentage renewable	1.1%		Derived from Haukoos (1995) and Campbell & Ohrt (2009)
Specific emergy	2.77E+09	sej/g	Haukoos, 1995
Total renewable quantity concrete	2.09E+04	g/year	
Total non-renewable quantity concrete	1.88E+06	g/year	
Total renewable emergy	5.79E+13	sej/year	
Total non-renewable emergy	5.21E+15	sej/year	

R6/P12 Dairy Feed

Quantity/cow * number cows * days/year * % (non)/renewable * specific emergy of dairy feed

Quantity per cow	41.8	kg/cow/day	BARC, 2011
Conversion factor	1000	g/kg	
Number of cows	105	cows	BARC, 2011
Days per year	365	days/year	
Renweable Component	14.2%		This study
Specific emergy of dairy feed	1.13E+10	sej/g	Brandt-Williams & Fodelberg, 2004
Total renewable dairy feed consumed	2.27E+08	g/year	
Total non-renewable dairy feed consumed	1.37E+09	g/year	
Total renewable emergy of dairy feed	2.57E+18	sej/year	
Total non-renewable emergy of dairy feed	1.56E+19	sej/year	

P1 Electricity

Quantity * energy content * solar transformity of standardized electricity

Quantity	9.33E+04	kWh/year	Our estimate
Joules per kilowatt hour	3.60E+06	J/KWh	
Transformity of standarized electricity	2.69E+05	sej/J	Odum, 1996, corrected by factor of 1.68 (Odum et al., 2000).
Total electricity consumed	3.36E+11	J/year	
Total emergy	9.04E+16	sej/year	

P3 Potable Water

Quantity/cow/day * number of cows * days/year * transformity of potable water

Quantity	32.3	gal/cow/day	Waldner & Looper, 2002
Gallon conversion	3.785	L/gal	
Number of cows	105	cows	BARC, 2011
Days per year	365	days/year	
Specific emergy	3.00E+08	sej/L	Buenfil, 2001
Total weight	4.69E+06	L/year	
Total emergy	1.17E+15	sej/L	

P6 Gravel (barn footers & pad)

Quantity/year * specific emergy of gravel

Quantity	4.67E+07	g/year	Our estimate
Specific emergy	1.30E+09	sej/g	Campbell et al., 2005
Total emergy	6.06E+16	sej/year	

P7 Aluminum (barn roofing)

Quantity/year * specific emergy of aluminum

Quantity	3.03E+01	g/year	Our estimate
Specific emergy of aluminum	1.81E+09	sej/g	Brown & Buranakarn, 2003
Total emergy	5.48E+10	sej/year	

P9 Diesel

Quantity * density * specific emergy of diesel

Quantity	1402	gal/year	Our estimate
Density of diesel	0.832	kg/L	
Gallon conversion	3.785	L/gal	
Kilogram conversion	1000	g/kg	
Specific emergy of diesel	2.83E+09	sej/g	Bastianoni et al., 2009
Total weight	4.41E+06	g/year	
Total emergy	1.25E+16	sej/year	

P10 Polyethylene (barn curtains)

Quantity/year * specific emergy of polyethylene

Quantity	3.60E+03	g/year	Our estimate
Specific emergy	8.85E+09	sej/g	Pulselli et al., 2007
Total emergy	3.19E+13	sej/year	

P11 Farm machinery

Weight of excavator & tractor * weighted transformity according to part composition / expected lifetime

Weight of Excavator	3400	kg	Bobcat Company, 2012
Weight of Tractor	7030	kg	Deere & Co., 2011
Kilogram conversion	1000	g/kg	
Lifetime of excavator	15	years	
Specific emergy of tractor	9.24E+09	sej/g	Weighted transformity of parts derived from Pulselli et al., 2007
Total weight	6.95E+05	g/year	
Total emergy	6.42E+15	sej/year	

P13 Copper wiring

Quantity of copper wire * specific emergy of copper

Quantity of 12AWG wire	2.46E+06	g/year	Our estimate
Specific emergy of copper	9.80E+10	sej/g	Cohen et al., 2007
Total emergy copper	2.41E+17	sej/year	

Y1 Milk

Avg. Production/cow/day * number of cows * days/year

Quantity per cow	40.0	kg/cow/day	Leith, 2011
Conversion factor	1000	g/kg	
Number of cows	105	cows	Leith, 2011
Days per year	365	days/year	
Total milk produced	1.53E+09	g/year	

Y2 Feces

Avg. Production/cow/day * number of cows * days/year

Quantity per cow	38.4	kg/cow/day	Our calculations
Conversion factor	1000	g/kg	
Number of cows	105	cows	Leith, 2011
Days per year	365	days/year	
Total feces produced	1.47E+09	g/year	

Y3 Urine

Avg. Production/cow/day * number of cows * days/year

Quantity per cow	16.6	kg/cow/day	Our calculations
Conversion factor	1000	g/kg	
Number of cows	105	cows	Leith, 2011
Days per year	365	days/year	
Total urine produced	6.36E+08	g/year	

Haitian Anaerobic Digestion Process

R1 Solar radiation

Solar incidence/m2/year * footprint of digesters * transformity of sunlight

Normal solar radiation for Cange, Haiti	5.15	kWh/m^2/year	Atmospheric Science Data Center, 2011
Footprint of digesters	16.8	m^2	
Conversion	3.60E+06	J/kWh	
Solar transformity of sunlight	1.00E+00	sej/J	By definition
Total sunlight energycontribution	3.11E+08	J/year	
Total Emergy of solar radiation	3.11E+08	sej	

R2 Groundwater

Volume of groundwater * density of groundwater * days per year * specific emergy of groundwater

Quantity of groundwater	585	L/day	Our calculations
Density of groundwater	1000	g/L	
Days per year	365	days/year	
Specific emergy of groundwater	1.14E+06	sej/g	Buenfil, 2001
Total renewable quantity feces	2.13E+08	g/year	
Total renewable emergy	2.43E+14	sej/year	

R3/P1 Labor and Maintanance

Hours of labor per year * work per hour labor * transformity of labor

Amount per year - digester	288	hr/year	Our estimate
Work done	3.45E+05	J/hr	Derived from UNFAO, 2012
Percentage renewable	18.3%		Derived from diet
Transformity of Labor	1.00E+07	sej/J	(Odum 1996) corrected by factor of 1.68 (Odum et al., 2000)
Total Joules labor per year	9.94E+07	J/year	
Total emergy of labor & maintenance	9.94E+14	sej/year	
Total renewable labor	1.53E+07	J/year	
Total non-renewable labor	8.41E+07	J/year	

R4/P2 Feces

Quantity of feces/day * density of feces * days/year * % (non)/renewable * specific emergy of feces

Quantity of feces	520	g/person/day	Polprasert, 2007
Number of people	291		
Days per year	365	days/year	
Proportion renewable	23.7%		This study
Specific emergy of feces	4.36E+09	sej/g	This study
Total renewable quantity feces	1.30E+07	g/year	
Total non-renewable quantity feces	4.21E+07	g/year	
Total renewable emergy	5.69E+16	sej/year	
Total non-renewable emergy	1.84E+17	sej/year	

R5/P3 Urine

Quantity of urine/day * density of urine * days/year * % (non)/renewable * specific emergy of urine

Quantity of urine	1	L/person/day	Polprasert, 2007
Number of people	291		
Density of urine	1200.0	g/L	Klatt, 2011
Days per year	365	days/year	
Proportion renewable	23.7%		This study
Specific emergy of urine	4.36E+09	sej/g	This study
Total renewable quantity feces	3.01E+07	g/year	
Total non-renewable quantity feces	9.72E+07	g/year	
Total renewable emergy	1.31E+17	sej/year	
Total non-renewable emergy	4.24E+17	sej/year	

P4 Polypropylene (PP) Digester Bags & Liners

Weight of PP * specific emergy of PP / lifetime of system

Weight of PP	56	kg	Eaton, A., 2011
Metric conversion	1000	g/kg	
Theoretical lifetime of system	10	years	Our estimate
Specific emergy of PP	9.86E+09	sej/g	From polyethylene (Pulselli et al., 2007)
Total quantity PP	5.60E+03	g/yr	
Total emergy	5.52E+13	sej/yr	

P5 PVC Piping

PVC weight per linear foot * linear feet * speicific emergy of PVC / lifetime of system

Weight	4.98E+05	g	Our estimate
Theoretical lifetime of system	10	years	Our estimate
Specific emergy of PVC	9.86E+09	sej/g	Pulselli et al., 2007
Total quantity PVC	4.98E+04	g/year	
Total emergy of PVC	4.91E+14	sej/year	

Y1 Biogas (as CH_4)

Methane production per day * energy content of methane * days per year

Production per day	3.81	m3/day	Our estimate
Metric conversion	1000	L/m3	
Energy content of methane	3.82E+04	J/L	
Days per year	365	day/year	
Total energy content of biogas	5.32E+10	J/year	

Y2 Nitrogen

(Quantity of N in influent - Quantity of N in influent * Avg. % N lost during AD from literature) * days per year

Quantity of nitrogen in influent	3.83	kg/day	Our calculations
Percent nitrogen lost during AD	7.0%		Schievano et al., 2011
Quantity of nitrogen in effluent	3.56	kg/day	
Metric conversion	1000	g/kg	
Days per year	365	day/year	
Total quantity of nitrogen	1.30E+06	g/year	

Y3 Phosphorus

(Quantity of P in influent - Quantity of P in influent * Avg. % P lost during AD from literature) * days per year

Quantity of phosphorous in influent (as P_2O_5)	0.89	kg/day	Our calculations
Percent phosphorous lost during AD	0.070		Schievano et al., 2011
Quantity of phosphorous in effluent	0.83	kg/day	
Metric conversion	1000	g/kg	
Days per year	365	day/year	
Total quantity of phosphorous	3.03E+05	g/year	

Y4 Non-potable water

(Water component of influent/day - water lost in biogas/day) * density of water * days per year

Liquid component of influent	1001	L/day
Water lost in biogas	0.7	L/day
Density of water	1000	g/L
Days per year	365	days/year
Total quantity of water	3.65E+08	g/year

Maryland Anaerobic Digestion Process

R1 Solar Radiation

Solar incidence/m2/year * surface area of manure pit * conversion factor to J * transformity of sunlight

Solar Insolation	3.84	kWh/m2/year	Atmospheric Science Data Center, 2011
Footprint of manure pit	23.2	m^2	
Conversion	3.60E+06	J/kWh	
Solar transformity of sunlight	1.00E+00	sej/J	By definition
Total sunlight energy contribution	3.21E+08	J/year	
Total Emergy of solar radiation	3.21E+08	sej/year	

R2/P2 Labor & Maintenance

Hours of labor per year * work per hour labor * transformity of labor

Amount per year	502.9	hr/year	Our estimate
Work done	6.43E+05	J/hr	Derived from UNFAO, 2012
Percentage renewable	4.9%		Taken from %R for U.S. (Campbell & Orht, 2009)
Transformity of Labor	1.00E+07	sej/J	(Odum 1996) corrected by factor of 1.68 (Odum et al., 2000)
Total labor renewable	1.58E+07	g/year	
Total labor non-renewable	3.07E+08	g/year	
Total emergy renewable	1.58E+14	sej/year	
Total emergy non-renewable	3.07E+15	sej/year	

R3/P8 Feces

Total manure volume * proportion feces * manure density * days per year * transformity of manure

Volume of Manure per day	137.4	gallons/day	Our estimate
Percent feces in manure	69.8%		ASAE, 2003; Our calculations
Density of Manure	3.76E+03	g/gallon	Barker et. al., 2001
Days per year	365	days/year	
Percentage renewable	13.1%		This study
Transformity of Manure	9.60E+09	sej/g	This study
Total mass renewable	1.73E+07	g/year	
Total mass non-renewable	1.14E+08	g/year	
Total emergy renewable	1.66E+17	sej/year	
Total emergy non-renewable	1.10E+18	sej/year	

R4/P9 Urine

Total manure volume * proportion urine * urine density * days per year * transformity of manure

Volume of Manure per day	137.4	gallons/day	Our estimate
Percent urine in manure	30.2%		ASAE, 2003; Our calculations
Density of urine	3.93E+03	g/gallon	Reece, 2009
Days per year	365	day/year	
Percentage renewable	13.1%		This study
Specific emergy of urine	9.60E+09	sej/g	This study
Total mass renewable	7.81E+06	g/year	
Total mass non-renewable	5.16E+07	g/year	
Total emergy renewable	7.49E+16	sej/year	
Total emergy non-renewable	4.96E+17	sej/year	

P1 Electricity

Kilowatt hour of electricity consumed * energy content per kilowatt hour * transformity of electricity

Amount of electricity used	1.04E+03	KWh/year	Our estimate
Joules per kilowatt hour	3.60E+06	J/KWh	
Transformity of standarized electricity	5.64E+05	sej/J	(Odum 1996) corrected by factor of 1.68 (Odum et al., 2000).
Total electricity consumed	3.73E+09	J/year	
Total emergy	2.11E+15	sej/year	

P3 Cast Iron Pumps

∑(Weight of pumps * transformity of cast iron) / lifetime of system

Manure Pit Pump (lbs)	3.95E+04	g	Zoeller, 2012
Manure Influent Pump (lbs)	1.50E+04	g	Zoeller, 2012
Effluent to Lagoon Pump (lbs)	3.95E+04	g	Zoeller, 2012
Recirculation Pump (lbs)	1.45E+04	g	Taco, 2012
Theoretical lifetime of system	20	years	Our estimate
Transformity of cast iron	1.74E+09	sej/g	Haukoos, 1994
Total quantity cast iron	5.42E+03	g/year	
Total emergy	9.44E+12	sej/year	

P4 Diesel

(Gallons/year * density of diesel * conversions * transformity of diesel) / lifetime of system

Excavation	60	gallons	Our estimate
Density of diesel	0.832	kg/L	
Gallon conversion	3.785	L/gal	
Kilogram conversion	1000	g/kg	
Lifetime of system	20	years	
Transformity of diesel	2.83E+09	sej/g	Bastianoni et al., 2009
Total weight	9.45E+03	g/year	
Total emergy	2.67E+13	sej/year	

P5 EPS foam insulation

(EPS weight per cubic foot * cubic feet * transformity) / lifetime of system

Weight per cubic foot	4.63E+02	g/ft3	
Cubic feet	1.12E+02	ft3	Our estimate
Theoretical lifetime of system	20	years	Our estimate
Transformity	8.85E+09	sej/g	Pulselli et al., 2007
Total quantity EPS	2.59E+03	g/year	
Total emergy	2.29E+13	sej/year	

P6 PEX tubing

(Cross-linked HDPE weight per linear foot * linear ft * transformity) / lifetime of system

Weight per linear foot	9.89E+01	g/ft	Rochow, 2006
Linear feet	160	ft	Our estimate
Theoretical lifetime of system	20	years	Our estimate
Transformity	8.85E+09	sej/g	Pulselli et al., 2007
Total quantity PEX	7.91E+02	g/year	
Total emergy	7.00E+12	sej/year	

P7 HDPE culverts

(HDPE weight per linear foot * linear ft * transformity) / lifetime of system

Weight per linear foot (60" dia. N-12 pipe)	2.05E+04	g/ft	ADS, 2012
Linear feet	40	ft	Our calculations
Theoretical lifetime of system	20	years	Our estimate
Transformity	8.85E+09	sej/g	Pulselli et al., 2007
Total quantity HDPE	4.10E+04	g/year	
Total emergy	3.63E+14	sej/year	

P10 PVC piping

(PVC weight per linear foot * linear feet * transformity) / lifetime of system

Weight per linear foot (2" pipe)	327	g/linear ft	Georg Fischer Harvel LLC, 2012
Weight per linear foot (3" pipe)	675	g/linear ft	Georg Fischer Harvel LLC, 2012
Linear feet of 2" pipe	40	linear ft	Our estimate
Linear feet of 3" pipe	125	linear ft	Our estimate
Theoretical lifetime of system	20	years	Our estimate
Transformity	9.86E+09	sej/g	Pulselli et al., 2007
Total quantity PVC	4.87E+03	g/year	
Total emergy	4.80E+13	sej/year	

P11 PVC digester bags

(Total digester bag surface area * density of bag * transformity of PVC) / lifetime of system

Surface Area of Bags	55.2	m2	Our calculations
Density of PVC membrane material	1.26E+03	g/m2	Filmtex, 2011
Theoretical lifetime of system	20	years	Our Estimate
Transformity of PVC	9.86E+09	sej/g	Pulselli et al., 2007
Total quantity PVC	3.48E+03	g/year	
Total emergy	3.43E+13	sej/year	

P12 Stainless steel heating tank

[(70% * weight of tank * transformity of steel) + (20% * weight of tank * transformity of chromium) + (10% * weight of tank * transformity of nickel)] / lifetime of system

Weight of Tank	4.13E+05	g	Our estimate
Theoretical lifetime of system	20	years	Our estimate
Transformity of Steel	6.97E+09	sej/g	Pulselli et al., 2007
Transformity of Chromium	1.52E+11	sej/g	Cohen et al., 2007
Transformity of Nickel	2.00E+11	sej/g	Cohen et al., 2007
Overall specific emergy	5.53E+10	sej/g	Derived from Cohen et al., 2007, & Pulselli et al., 2007
Total quantity stainless steel	2.07E+04	g/year	
Total emergy	1.14E+15	sej/year	

P13 Solids Separator

((Weight of stainless steel * specific emergy of stainless steel) + (weight of cast iron * specific emergy of cast iron)) / lifetime of system

Weight of steel	2.50E+05	g	FAN Engineering
Weight of cast iron	2.50E+05	g	FAN Engineering
Theoretical lifetime of system	20	years	Our estimate
Transformity of 316 Stainless Steel	5.53E+10	sej/g	Pulselli et al., 2007
Transformity of cast iron	1.74E+09	sej/g	Haukoos, 1994
Total quantity material	2.50E+04	g/year	
Total quantity stainless steel	1.25E+04	g/year	
Total quantity cast iron	1.25E+04	g/year	
Total emergy	7.13E+14	sej/year	

P14 Copper wiring

Length of wire * density of wire * specific emergy of copper / lifetime of system

Length of 12 AWG wire	2000	ft	Our estimate
Density of wire	0.0198	lbs/ft	Office of Engineering Standards, 1966
Conversion	453.59	g/lbs	
Theoretical lifetime of system	20	years	Our estimate
Specific emergy of copper	9.80E+10	sej/g	Cohen et al., 2007
Total quantity copper	8.98E+02	g/year	
Total emergy copper	8.80E+13	sej/year	

P15 Brozne pump

[(80% * weight of pump * transformity of copper) + (10% * weight of pump * transformity of tin) + (10% * weight of pump * transformity of lead)] / lifetime of system

Weight of water pump	2.72E+03	g	Taco, 2012
Theoretical lifetime of system	20	years	Our estimate
Specific emergy of copper	9.80E+10	sej/g	Cohen et al., 2007
Specific emergy of tin	1.68E+12	sej/g	Cohen et al., 2007
Specific emergy of lead	4.80E+11	sej/g	Cohen et al., 2007
Overall specific emergy	2.94E+11	sej/g	Derived from Cohen et al., 2007
Total quantity stainless steel	1.36E+02	g/year	
Total emergy	4.01E+13	sej/year	

Y1 Biogas (as CH_4)

(Volume manure/day * density of manure * biogas production/day * days per year * energy content of methane) - energy used per year

Volume of Manure per day	137.4	gallons/day	Our estimate
Volume conversion	3.79E+03	mL/gallon	
Density manure	1.2	g/mL manure	
Production per day	11.2	mL CH4/g man	Our research
Metric conversion	0.001	L/mL	
Energy content of methane	3.82E+04	J/L	
Days per year	365	day/year	
Total energy content of biogas produced	9.76E+10	J/year	
Total energy content of biogas used	3.02E+10	J/year	
Total energy content of biogas	6.74E+10	J/year	

Y2 Bedding

Volume effluent/day * density of manure * TS of digester effluent * days per year

Volume of Manure per day	137.4	gallons/day	Our estimate
Volume conversion	3.79E+03	mL/gallon	
Density manure	1.2	g/mL manure	
Total solids of digestate	36.9	mg/g	Our research
Metric conversion	1.00E-03	g/mg	
Days per year	365	day/year	
Total weight solids	8.41E+06	g/year	

Y3 Nitrogen

Volume effluent/day * quantity TKN in effluent * days per year

Quantity effluent per day	134.8	gallons/day	Our calculations
Conversion	3.785	L/gallon	
Quantity of nitrogen in effluent	1954	mg/L	Our data
Metric conversion	0.001	g/mg	
Days per year	365	day/year	
Total quantity of nitrogen	3.64E+05	g/year	

Y4 Phosphorus

Volume effluent/day * quantity TP in effluent * days per year

Quantity effluent per day	134.8	gallons/day	Our calculations
Conversion	3.785	L/gallon	
Quantity of phosphorus in effluent	260	mg/L	Our data
Metric conversion	0.001	g/mg	
Days per year	365	day/year	
Total quantity of phosphorous	4.84E+04	g/year	

Y5 Non-potable water

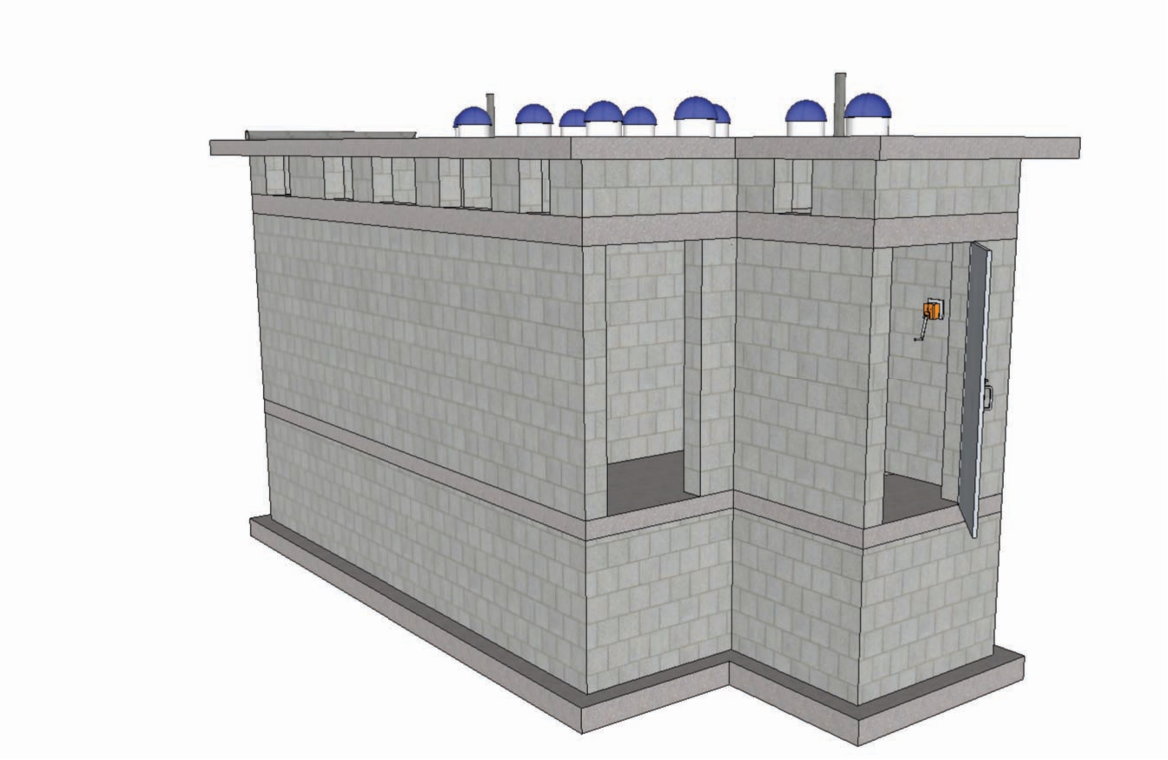
Volume effluent/day * proportion that is water * density of water * days per year

Quantity effluent per day	134.8	gallons/day	Our calculations
Percent water in effluent	96.4%		Our data
Conversion	3.785	L/gallon	
Density of water	1000	g/L	
Days per year	365	day/year	
Total quantity of water	1.80E+08	g/year	

APPENDIX B: HAITIAN LATRINE DESIGNS

Zanmi Lasante External Clinic Latrine and Flush System

Providing waste conveyance to the hospital's new anaerobic digestion system



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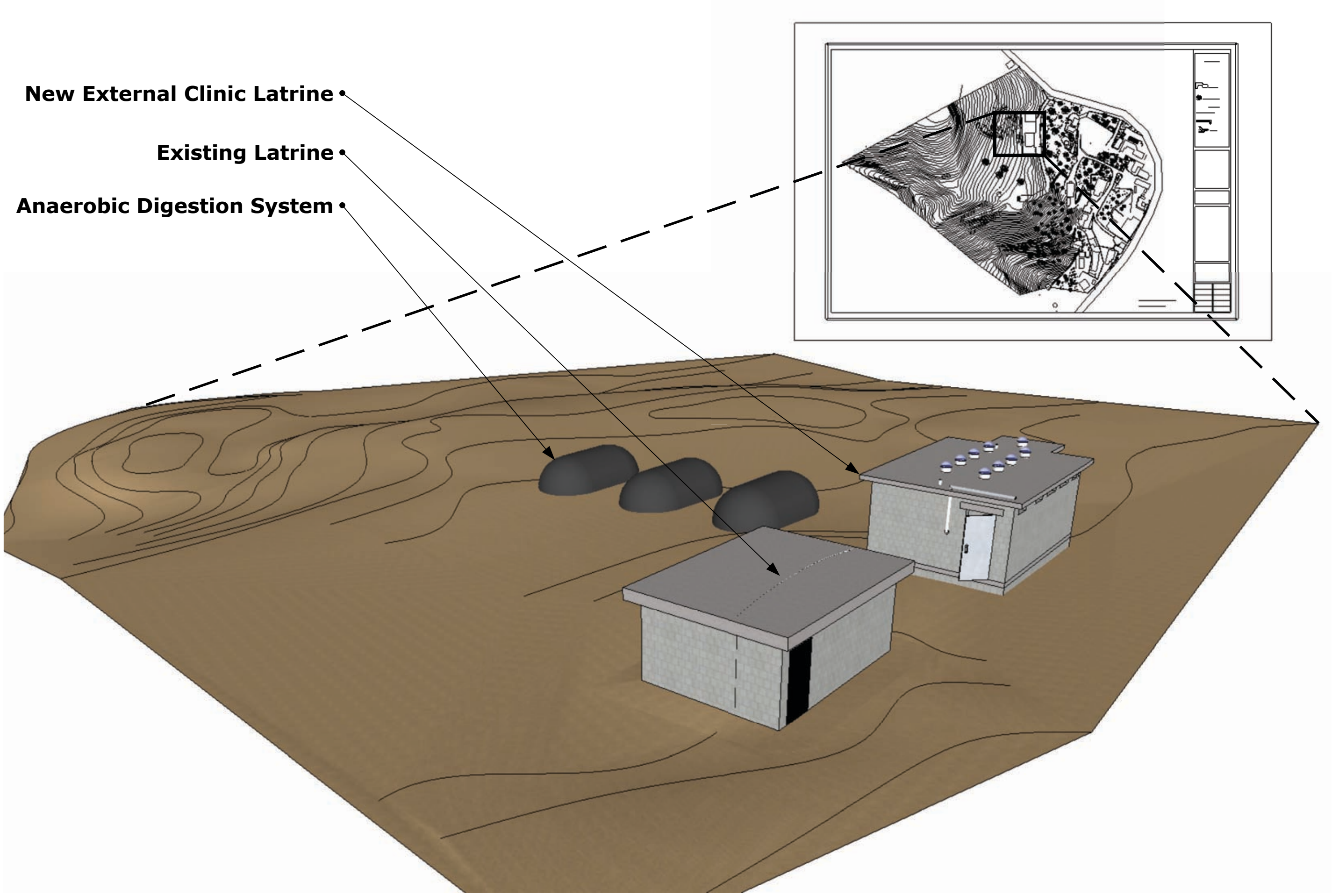
CLIENT	PROJECT	PROJECT NO.	DRAWN BY	ISSUE
Zanmi Lasante Cange, Haiti	Haiti External Clinic Latrine	July 2011 Submission	Andy Moss	06.28.11

Latrine Overview

A.001



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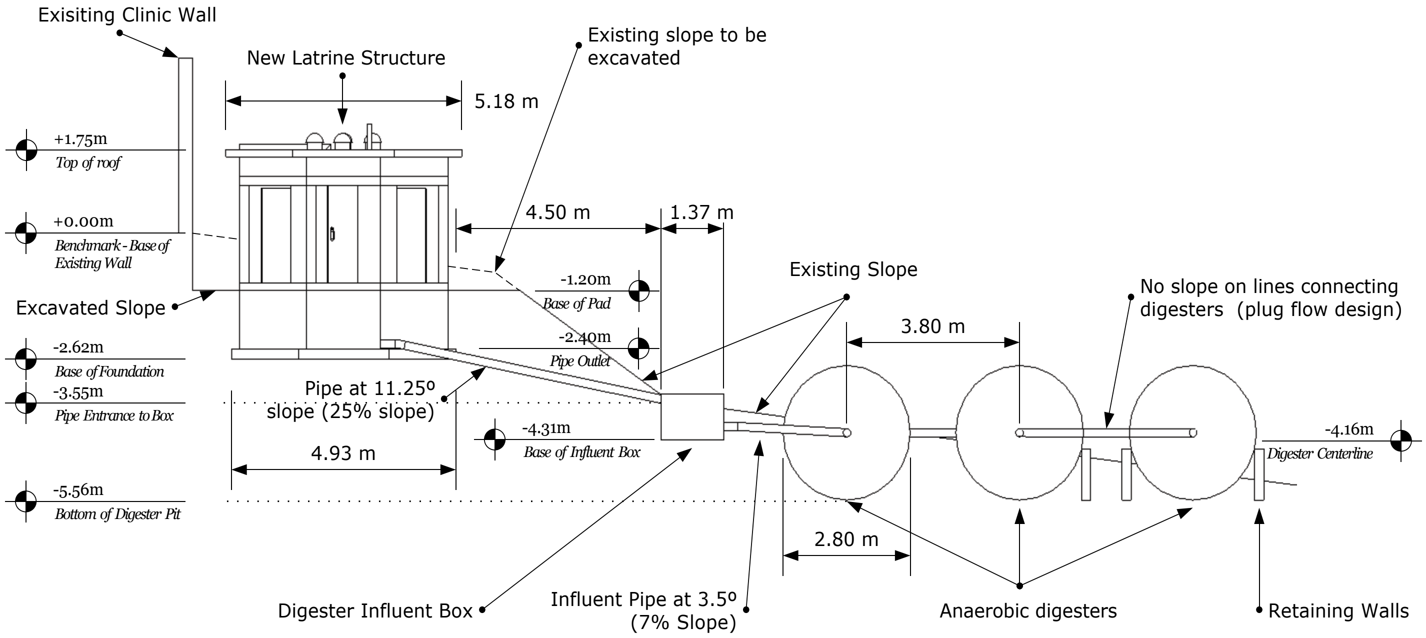
Site Overview
A.002

Zanmi Lasante Flushing Latrine and Anaerobic Digestion System

Capacity - 600 people/day

Process - Solid human waste and black water from the new latrine structure will channel down through a conveyance and screening system to the latrine pipe outlet. This will flow into the digester influent box - a catchment box where cow manure and other materials may be added to facilitate the system - and then be directed into a series of 2.8m diameter, 4m long, nearly cylindrical digesters (total liquid capacity - 12m^3).

Products - The generation of methane from the digesters will offset the Zanmi Lasante hospital cooking fuel costs - roughly $1,600 U.S. per month. In addition, the digester effluent will provide an abundant fertilizer source for local agriculture, including mango stands.



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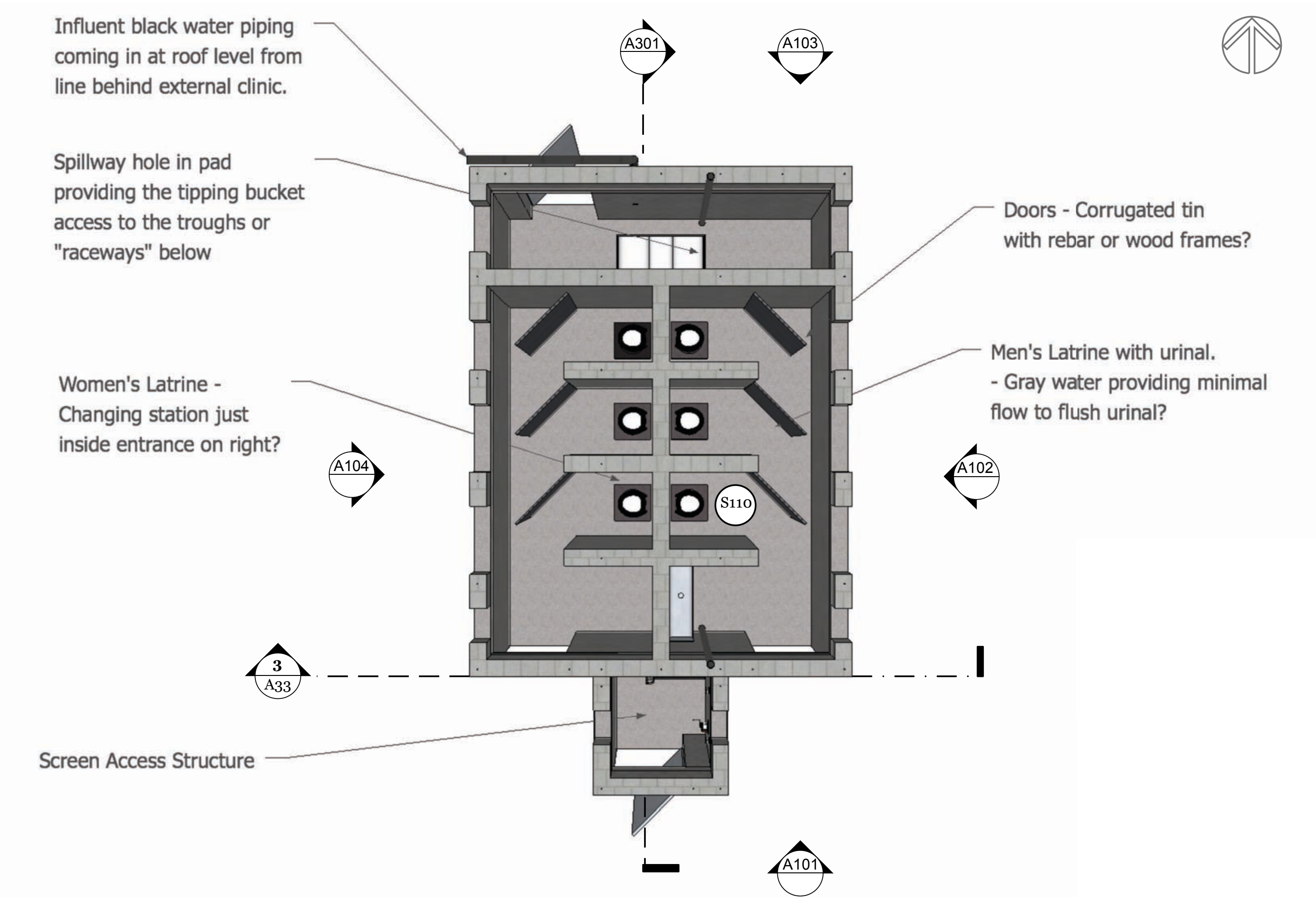
Zanmi Lasante Cange, Haiti	Haiti External Clinic Latrine	July 2011 Submission	Andy Moss	06.28.11

Site Elevations
A.003



Influent black water piping coming in at roof level from line behind external clinic.

Spillway hole in pad providing the tipping bucket access to the troughs or "raceways" below

Women's Latrine - Changing station just inside entrance on right?

Screen Access Structure

Doors - Corrugated tin with rebar or wood frames?

Men's Latrine with urinal.
- Gray water providing minimal flow to flush urinal?

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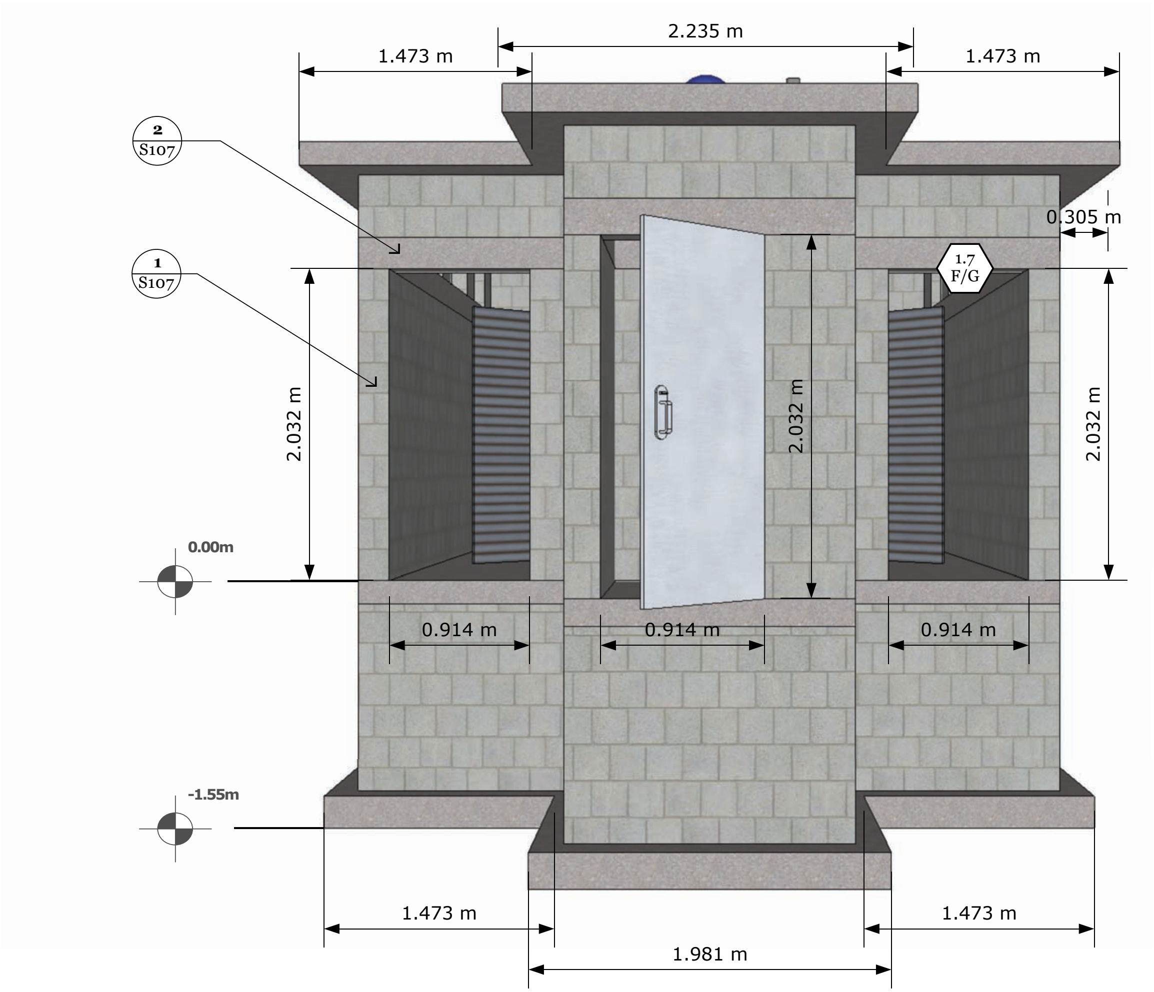
Latrine Floor Plan
A.004



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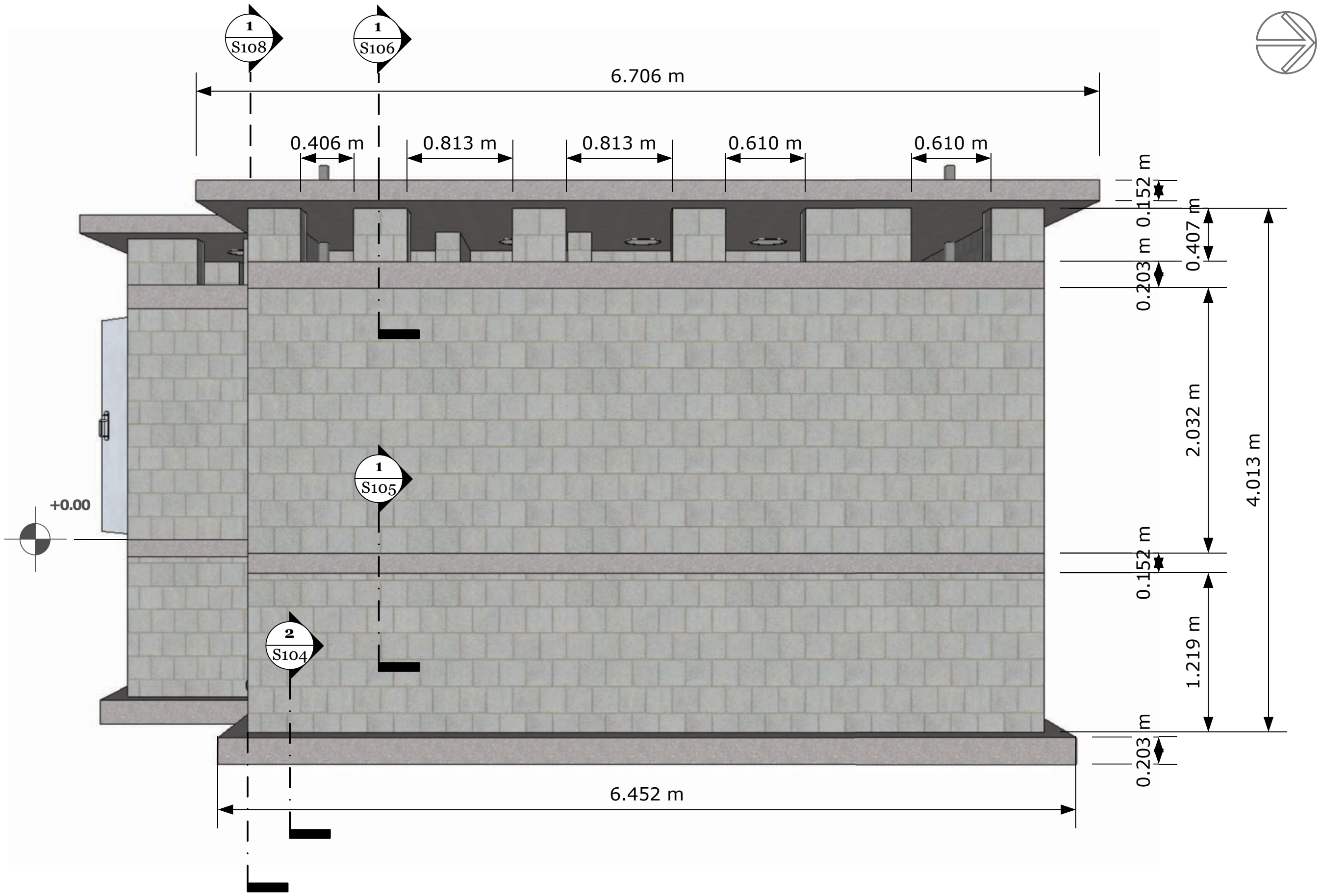
Zanmi Lasante Cange, Haiti	Haiti External Clinic Latrine	July 2011 Submission	Andy Moss	06.28.11

South Side Profile

A.101



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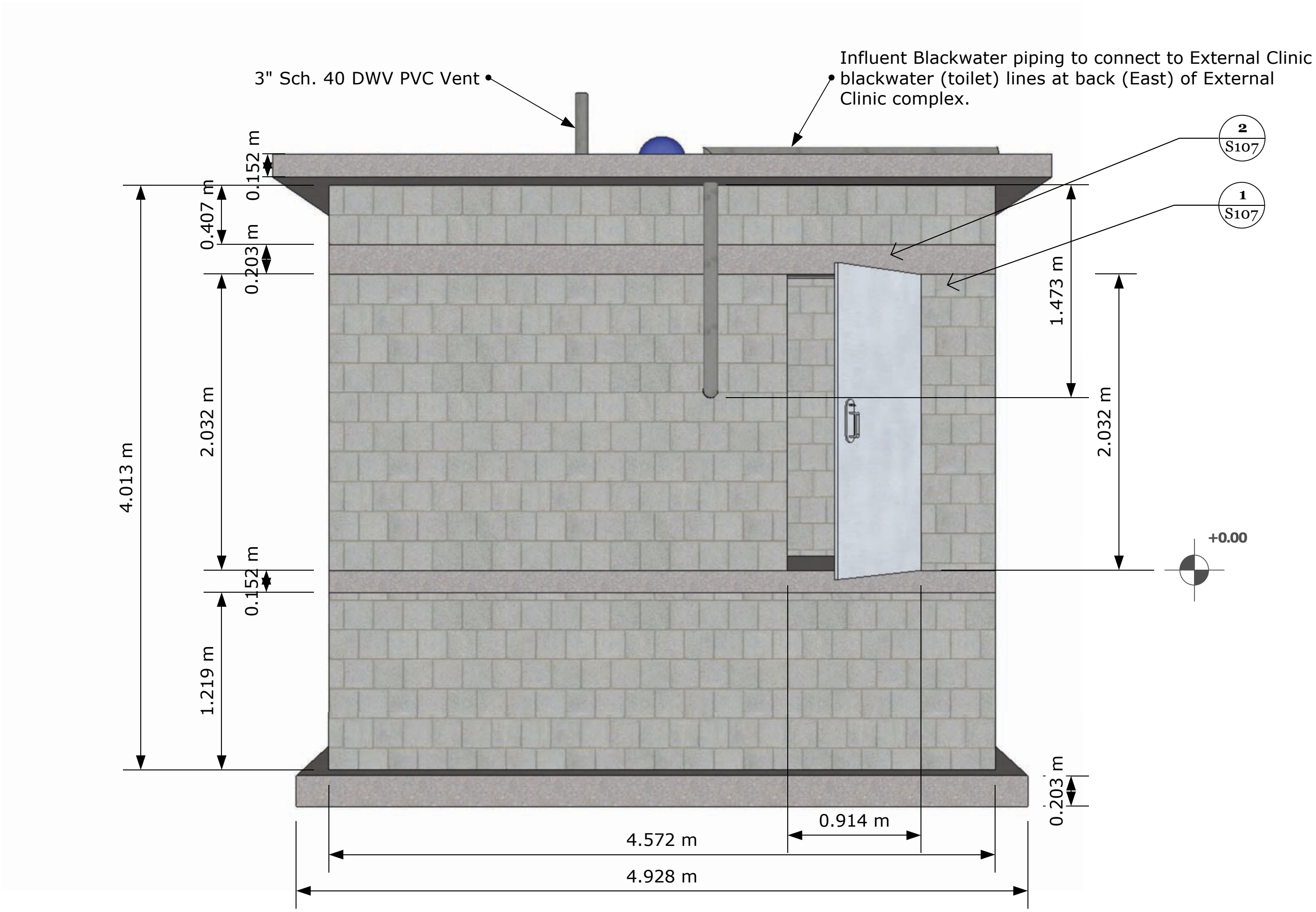
Zanmi Lasante Cange, Haiti	Haiti External Clinic Latrine	July 2011 Submission	Andy Moss	06.28.11

East Side Profile

A.102



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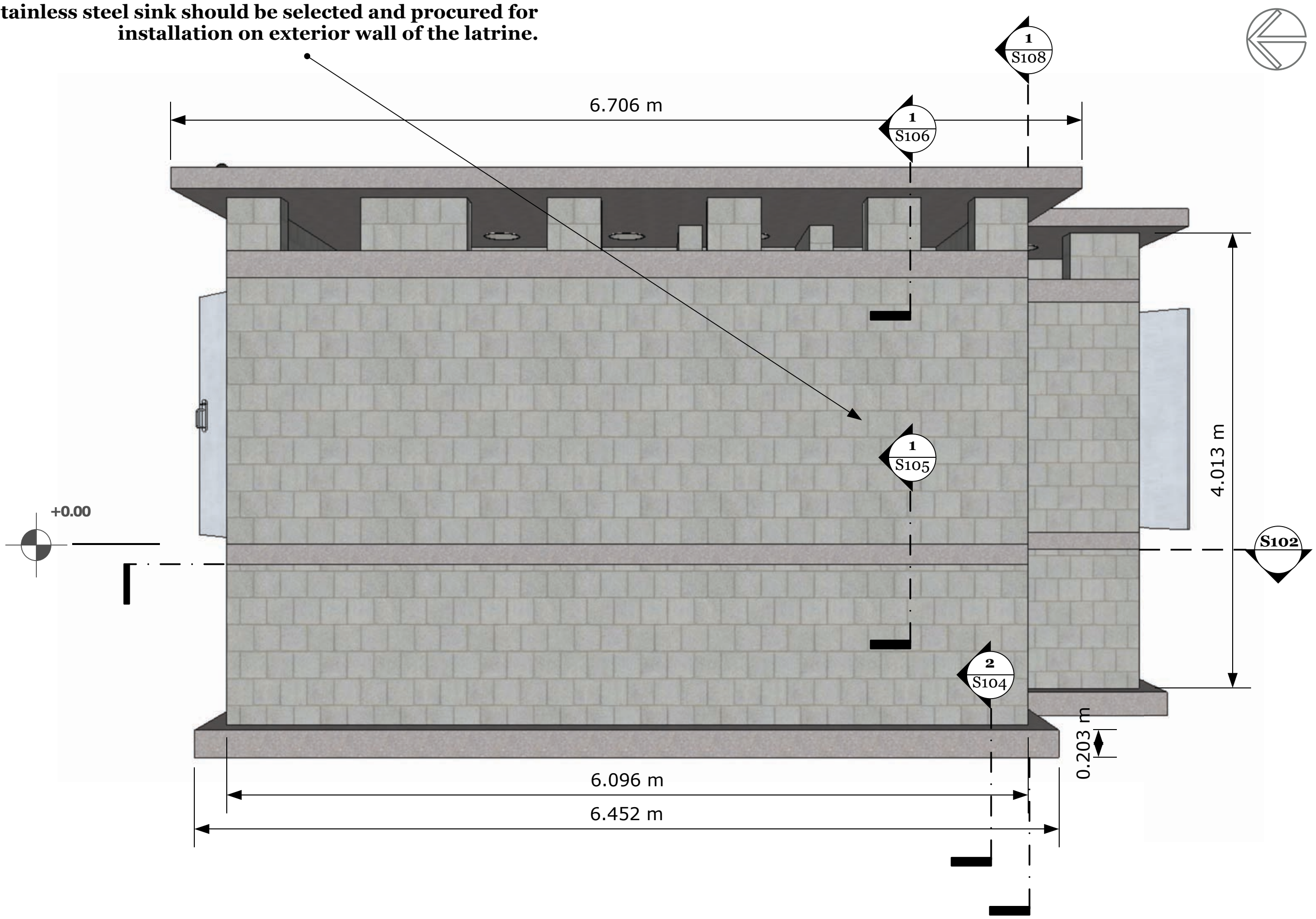
Zanmi Lasante Cange, Haiti	Haiti External Clinic Latrine	July 2011 Submission	Andy Moss	06.28.11

North Side Profile

A.103

Stainless steel sink should be selected and procured for installation on exterior wall of the latrine.



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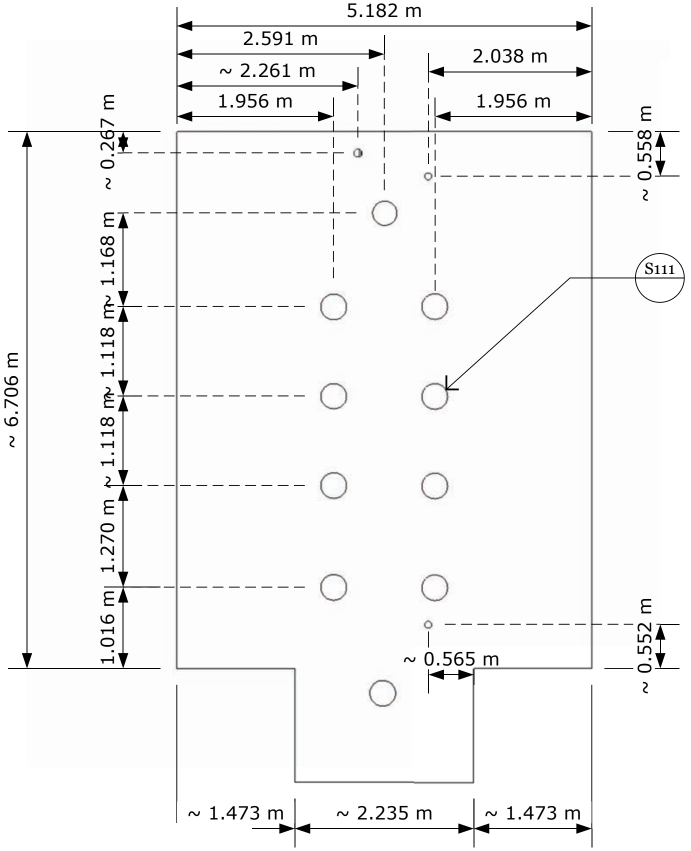
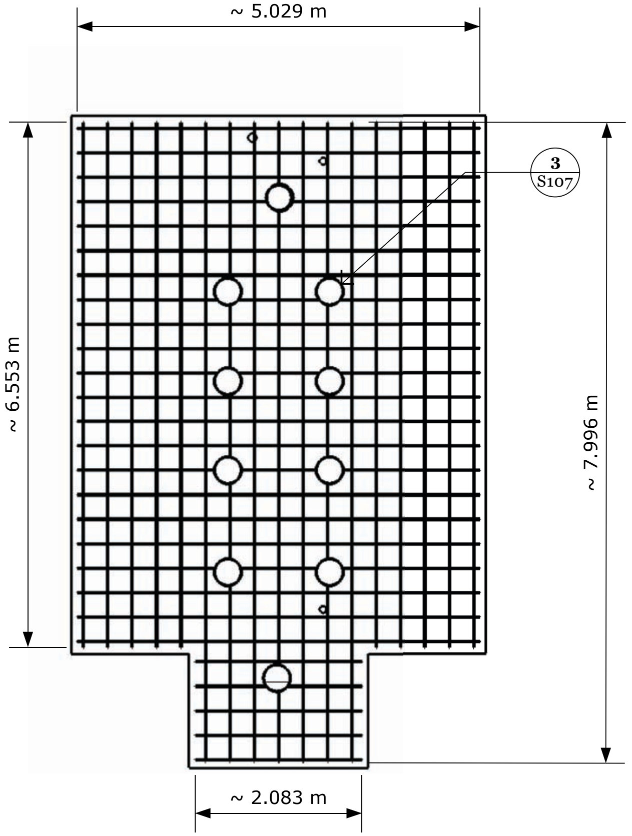
Zanmi Lasante Cange, Haiti	Haiti External Clinic Latrine	July 2011 Submission	Andy Moss	06.28.11

West Side Profile
A.104

NOTES:

1) All rebar is #4 standard (#13 metric) and is spaced 12" on center (.305 m) unless otherwise noted (ACI318-05 13.3 - Table 9.5).
2) All rebar MUST be placed 3" (0.076 m) on center from all external surfaces (e.g. concrete pads, lintel exteriors, etc.) (ACI 530-95 8.4.1).
3) All measurements to holes are roof edge to center.





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CLIENT	PROJECT	PROJECT NO.	DRAWN BY	ISSUE
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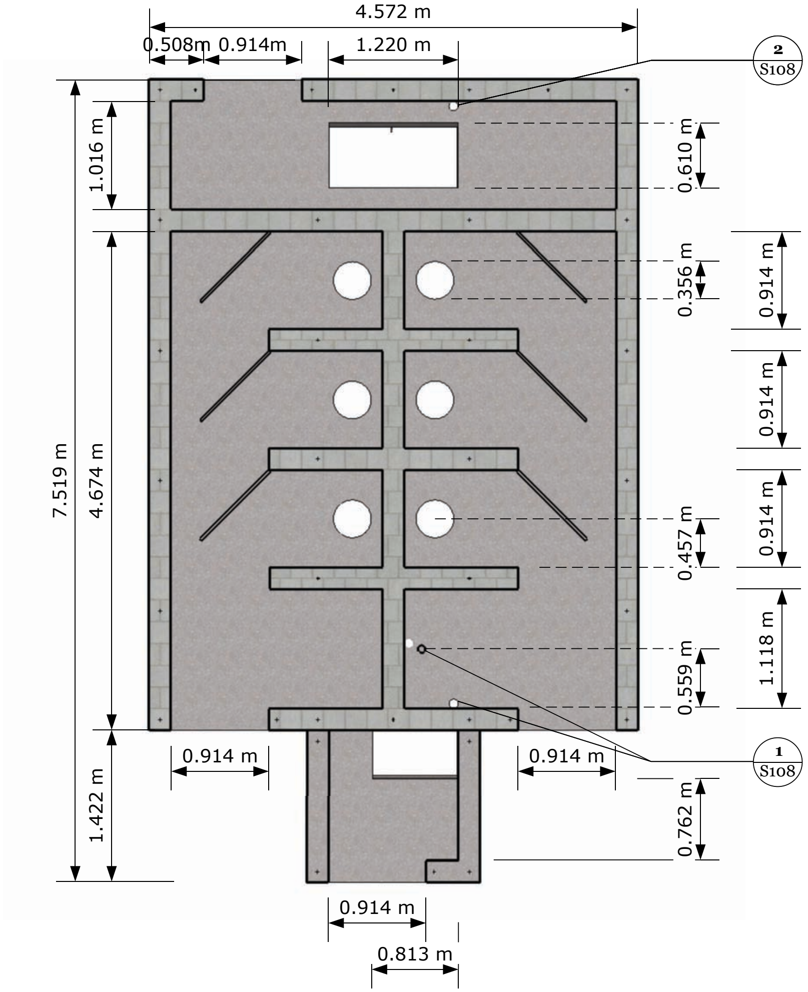
Roof Footprint & Details

A.105



Notes
- All walls are 8" x 8" x 16" concrete masonry units (1000 psi) - *ACI530-95/ASTM C90.*

- Two-way slab is 4000 psi concrete reinforced by a #4 rebar (#13 metric) grid spaced a minimum of 12" (0.304 m) on center.

- See General Notes - Sections 1.6, 1.7, & 1.8 for more detail.

Holes:

- All rebar should stop 3" short of all holes in slab and tie into rebar collar surrounding them (Details on S.106) (ACI 8.4.1).

- Hole in northernmost room is 2' x 4' (0.610m x 1.220m) and allows for conveyance of black water to raceways via a tipping bucket.

- Holes in individual stalls are 14" (0.356 m) in diameter and allow for conveyance of excrement to raceways.

- Hole in men's urinal is 3.50" (0.089 m) in diameter and should be formed by 3"ID Sch.40 PVC.

- Hole in screen room pad is 1' 6" x 2' 8" (0.457m x 0.813m) and provides ladder access to screen.

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CLIENT	PROJECT	PROJECT NO.	DRAWN BY	ISSUE
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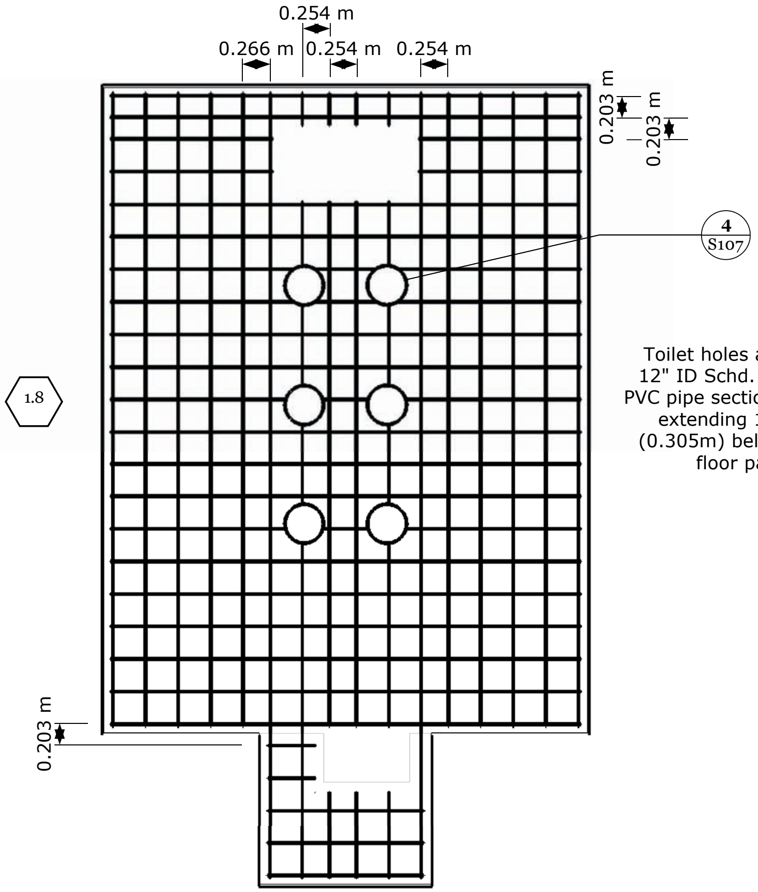
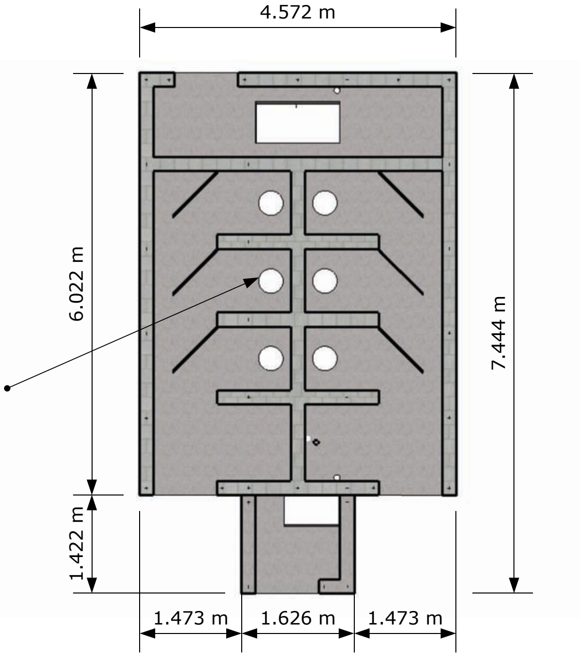
Floor Plan & Pad Details

A.106





Toilet holes are 12" ID Schd. 40 PVC pipe sections extending 12" (0.305m) below floor pad.

NOTES

- Rebar grid is #4/#13 rebar spaced 12" (0.305 m) on center unless otherwise noted

- Rebar should be positioned 3" from all surfaces on the 6" concrete pad (ACI 530 8.4.1)

- Anchor ties securing block to floor pad are 3' long x 1' handle (0.914 m x 0.305 m) and constructed of #4 (#13 metric) rebar. They should tie block walls to pad at all locations of vertical reinforcement.

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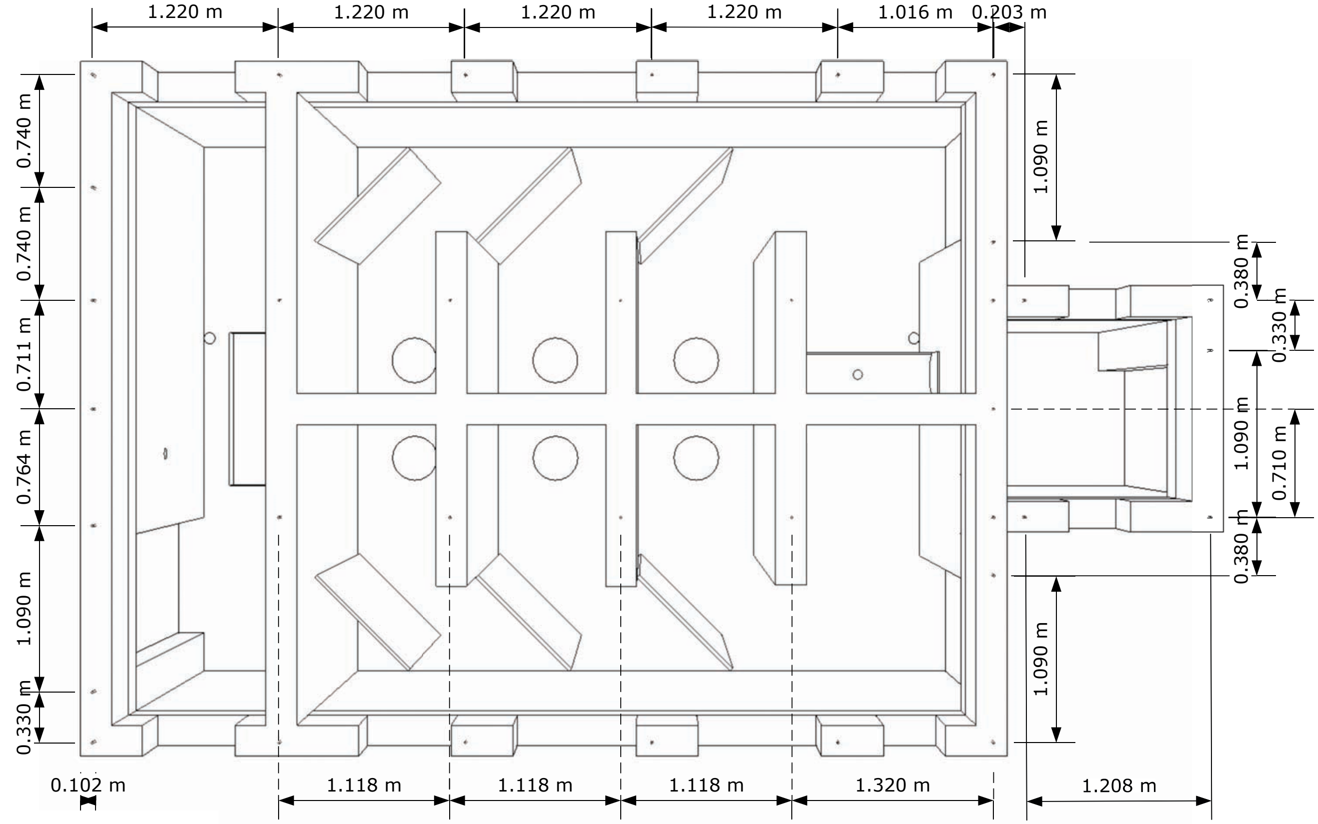
CLIENT	PROJECT	PROJECT NO.	DRAWN BY	ISSUE
Zanmi Lasante Cange, Haiti	Haiti External Clinic Latrine	July 2011 Submission	Andy Moss	06.28.11

Floor Pad Reinforcement

A.107

- All vertical reinforcement provided by Grade 60 #4 rebar (#13 metric).
- All rebar centered 4" (0.102 m) from nearest edges of 8" x 8" x 16" CMUs.
- Where vertical reinforcement is provided, pea gravel concrete or grout should be poured through CMUs to form reinforced columns. See General Notes - Section 1.6.
- Rebar extends **4" (0.102m) into foundation footers** and **3" into roof slab.**
- Vertical reinforcement anchored by 3' x 1' (0.305m x 0.914m) L-hook (#4 rebar - #13 metric) to ALL footers and slabs.



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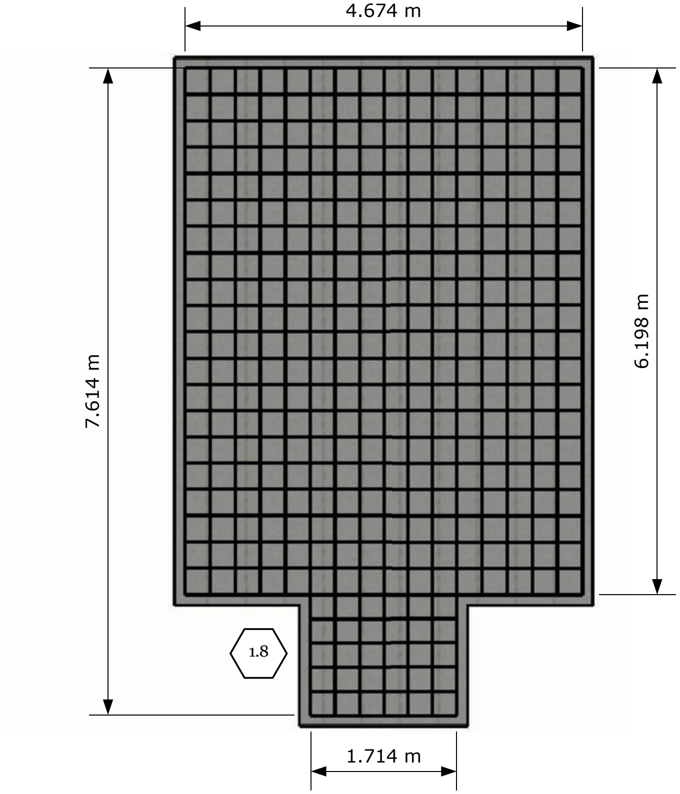
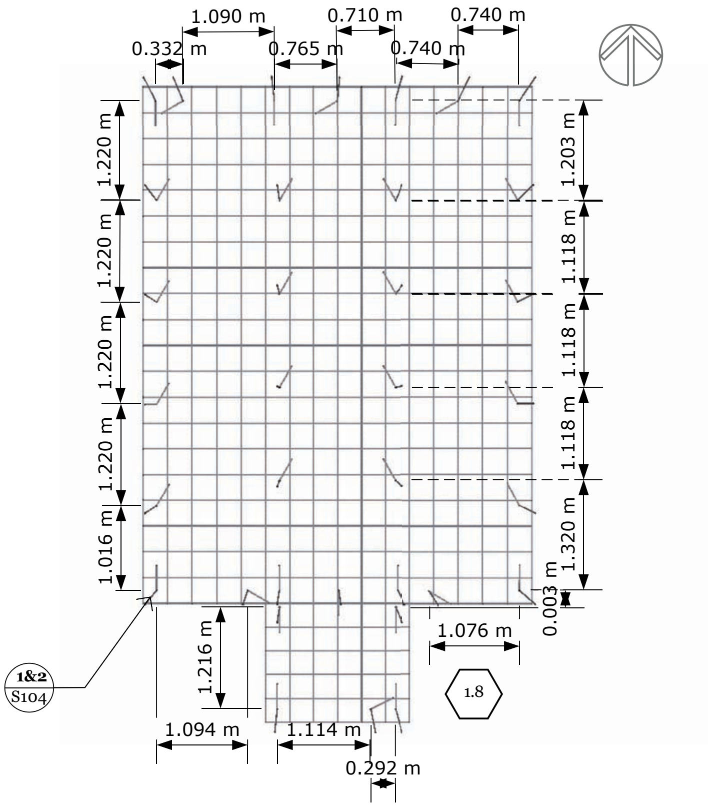
CLIENT	PROJECT	PROJECT NO.	DRAWN BY	ISSUE
Zanmi Lasante Cange, Haiti	Haiti External Clinic Latrine	July 2011 Submission	Andy Moss	06.28.11

Vertical Reinforcement Details

A.108





NOTES:

- All rebar in horizontal grid is #4/#13, Grade 60 spaced 12" (0.305m) on center.

- Foundation anchors are 3' long x 1' handle (0.914 m x 0.305 m) and constructed of #4 (#13 metric) rebar. Each anchor is tied to vertical reinforcing rebar with 16-gauge rebar tie wire and should be set 4" into foundation slab and tied to horizontal reinforcement. **See page S104.**

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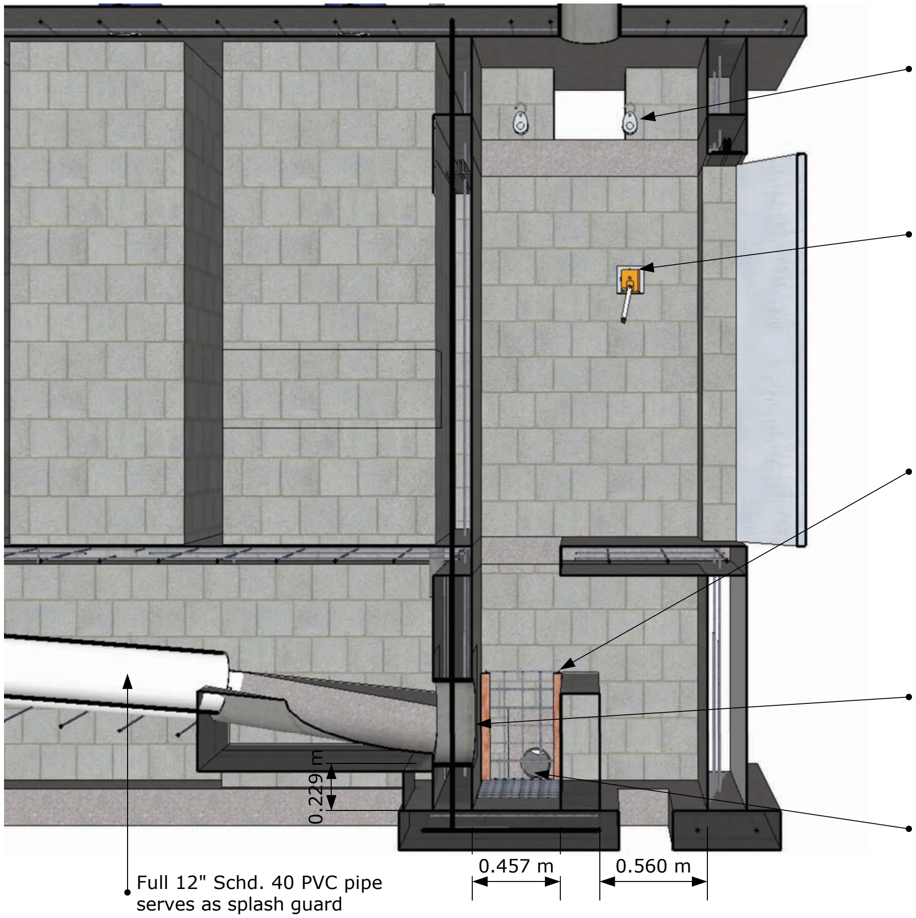
CLIENT	PROJECT	PROJECT NO.	DRAWN BY	ISSUE
Zanmi Lasante Cange, Haiti	Haiti External Clinic Latrine	July 2011 Submission	Andy Moss	06.28.11

Footer Reinforcement & Ties

A.109



Pulley system guiding and facilitating 3/16" stainless steel cable required for lifting

Hand winch/windlass system controlling raising and lowering of bar screen/basket system.

Winch mounted on metal plate situated 12" (0.305 m) from wall, or sufficiently spaced to allow for handle to be turned.

#4 (#13 metric) rebar screen welded in 4" x 4" (0.102m x 0.102m) grid and guided by 2' (0.610 m) sections of 2" (0.508 m) angle iron.

- Dimensions: Top - 16" Wide x 24" Tall (0.406m x 0.610m); Bottom - 17" Wide x 12" Long (0.432m x 0.305m).

- Bottom "basket" is #3 (#10 metric) rebar welded in 2" x 2" (0.051m x 0.051m) grid

18" ID Sch. 40 PVC outlet pipe is situated 9" (0.229 m) from floor (foundation) and is encased by 24" Wide x 24" Tall x 8" Deep (0.610m x 0.610m x 0.203m) concrete collar.

Bottom of 6" (0.152 m) SDR or Sch. 40 PVC outlet pipe is situated 1" from floor.

Full 12" Schd. 40 PVC pipe serves as splash guard

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CLIENT	PROJECT	PROJECT NO.	DRAWN BY	ISSUE
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Screen Structure Details

S.101

12" ID Sch. 40 PVC pipe rests on edges of 18" raceway half-pipes and is prevented from slipping forward by concrete confluence. **Joints between 12" and 18" pipe should be sealed with standard silicone caulk.**

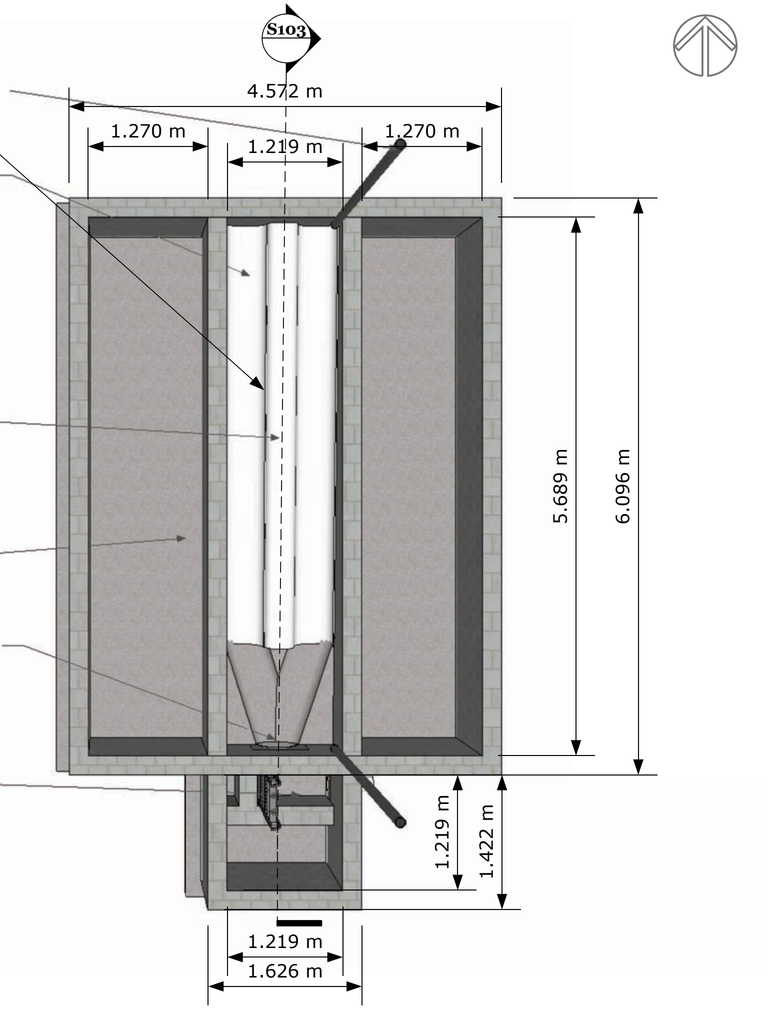
- Raceways are 18" Schedule 40 PVC, cut in half and turned face up.
- Pipes cut into 15' lengths, lain at 10% (4.5º) slope
- Supported underneath by rebar cross-stays running between the interior stem walls
- Prevented from sliding forward by the poured concrete "confluence" form at the bottom of the pipes.

Splash guard is 12" ID smooth exterior pipe, affixed to raceways with solvent adhesive and prevented from sliding by concrete confluence

Space between interior footers may be backfilled to provide additional support to the latrine floor slab.

Confluence is poured, shaped concrete. Effluent piping is an 8" section of the remaining 5' section of 18" Schedule 40 PVC pipe.

Screen sluice box is 33" L x 18" W x 24" H. Ladder provides access to the bar screen area and the raceways outflow piping.



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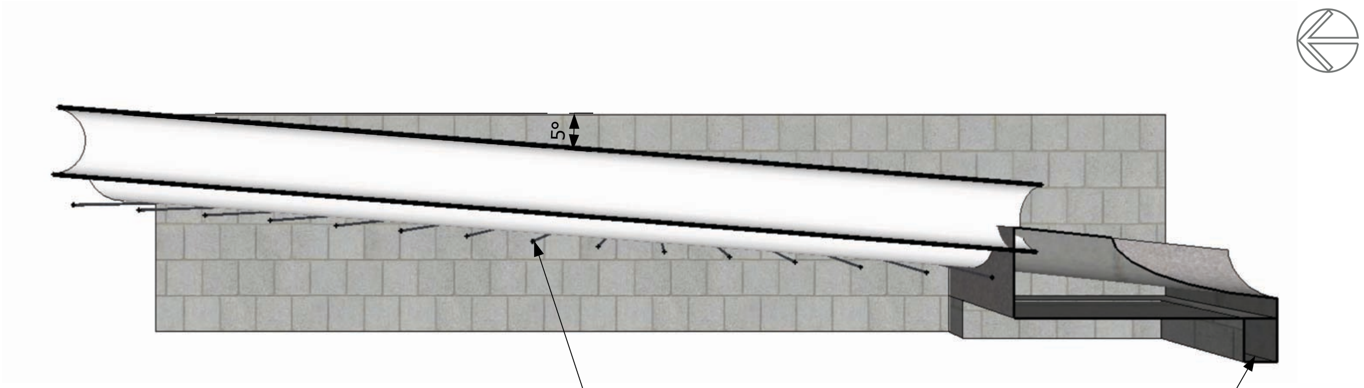
CLIENT	PROJECT	PROJECT NO.	DRAWN BY	ISSUE
Zanmi Lasante Cange, Haiti	Haiti External Clinic Latrine	Eng. Summit Submission	Andy Moss	06.28.11

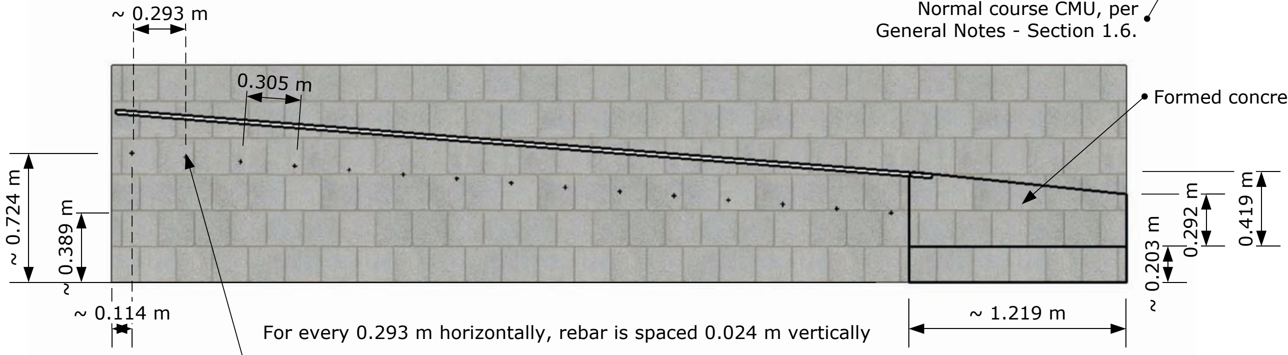
Raceway Overview

S.102



Half-pipes rest on rebar cross-stays and are prevented from sliding forward by concrete confluence structure

Normal course CMU, per General Notes - Section 1.6.



Formed concrete

For every 0.293 m horizontally, rebar is spaced 0.024 m vertically

#4 rebar (#13 metric) spaced 1' (0.305m) on center on a 5º (10%) slope

Rebar should extend 4" into stem walls on either side of raceway structure

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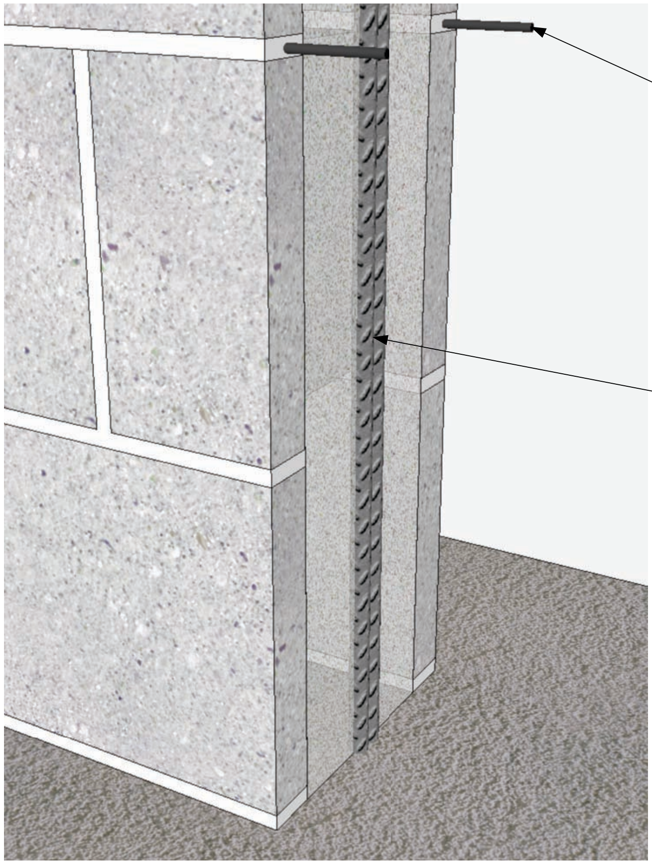
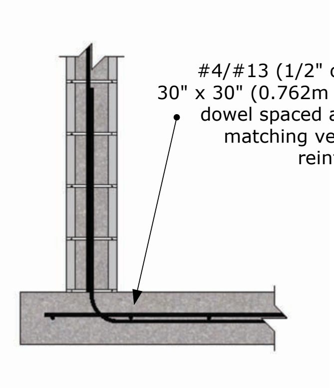
Raceway Profile & Details
S.103

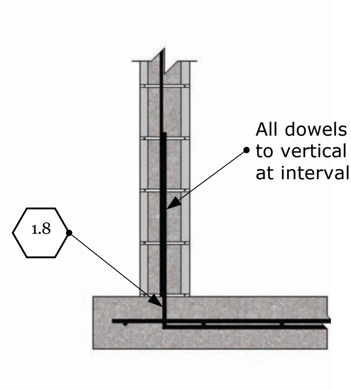


All rebar is #4 (#13), Grade 60 unless otherwise noted. See General Notes



#4/#13 (1/2" or 1.27cm) 30" x 30" (0.762m x 0.762m) dowel spaced at intervals matching vertical steel reinforcement.

1
S104
Foundation Anchor & Tie-in
Scale: 1mm : 20mm



All dowels should be tied to vertical reinforcement at intervals of 4" (0.102m)

2
S104
Foundation Anchor & Tie-in
Scale: 1mm : 20mm

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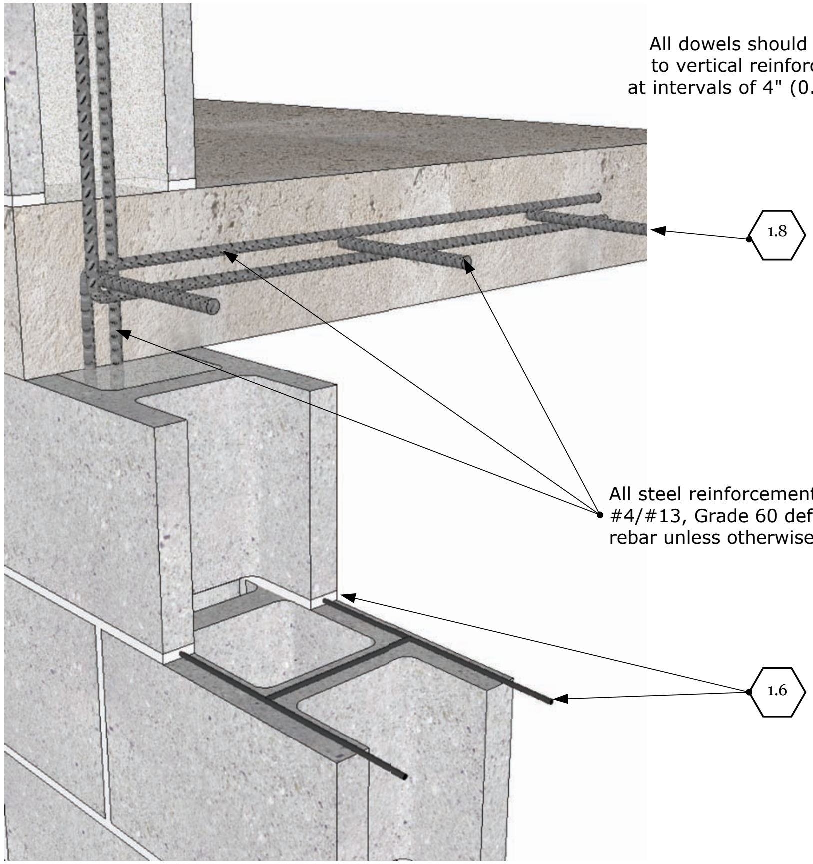
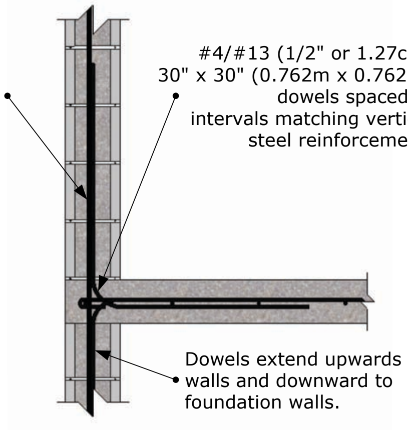
Foundation Tie-In
S.104



All steel reinforcement is #4/#13, Grade 60 deformed rebar unless otherwise noted.

Horizontal steel reinforcement shall be installed every two (2) vertical courses.



All dowels should be tied to vertical reinforcement at intervals of 4" (0.102m)

#4/#13 (1/2" or 1.27cm) 30" x 30" (0.762m x 0.762m) dowels spaced at intervals matching vertical steel reinforcement.

Dowels extend upwards to latrine walls and downward to foundation walls.

1
S105

Floor Pad Anchor and Tie-In

Scale: 1mm : 20mm

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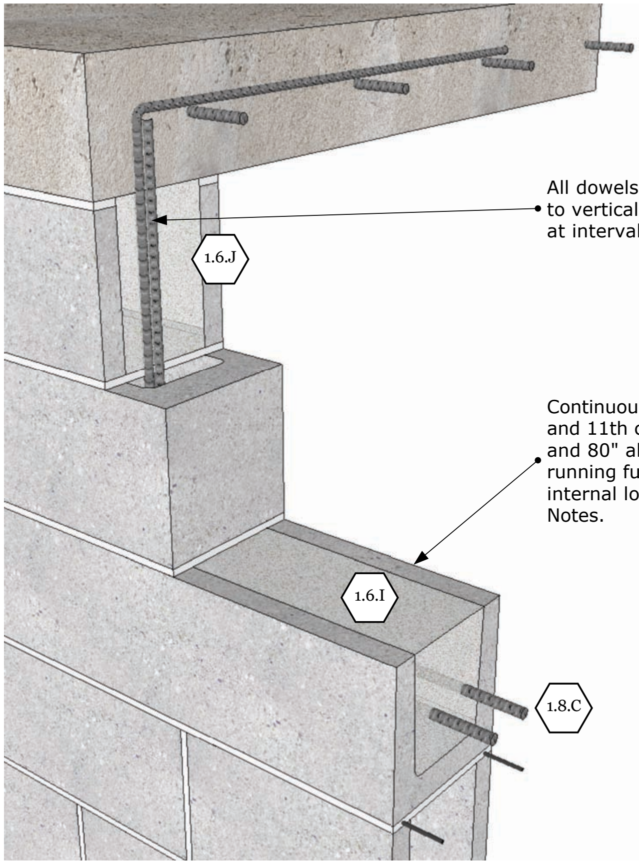
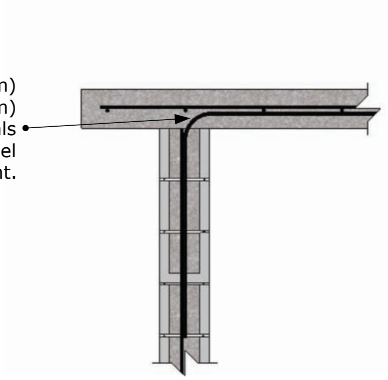
Floor Pad Tie-In
S.105



All dowels should be tied
to vertical reinforcement
at intervals of 4" (0.102m)

Continuous bond beams on 7th course
and 11th course (beginning at 48"
and 80" above top of floor pad)and
running full exterior of structure and
internal load-bearing wall. See General
Notes.



#4/#13 (1/2" or 1.27cm)
30" x 30" (0.762m x 0.762m)
dowel spaced at intervals
matching vertical steel
reinforcement.

1
S106

Roof Tie-In

Scale: 1mm : 20mm

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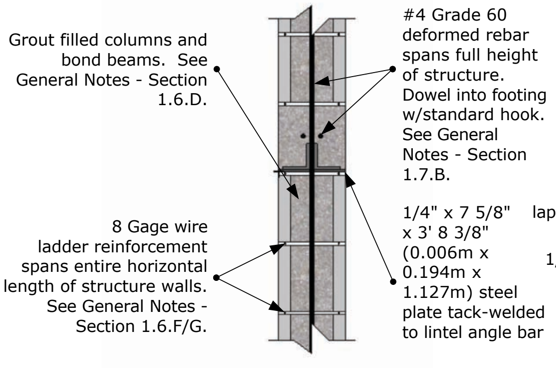
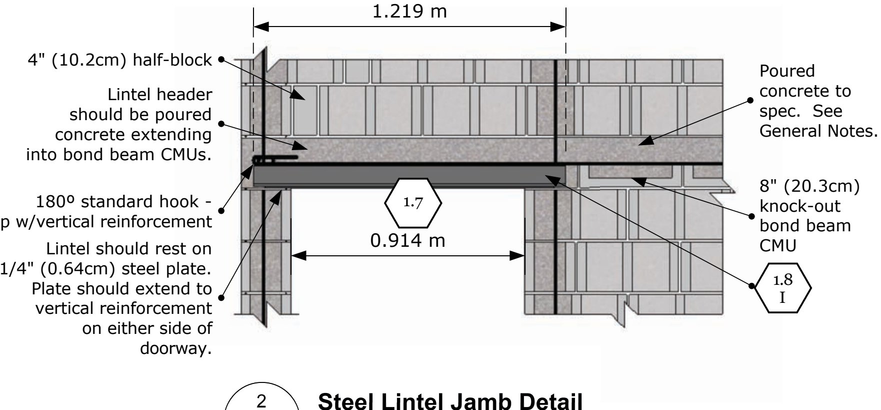
Roof Tie-In
S.106



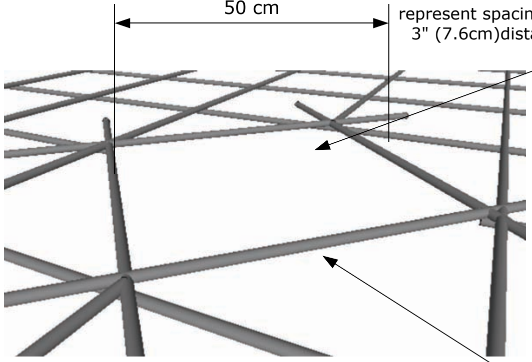
1 S107 **Steel Lintel Jamb Section**

Scale: 1mm : 15mm



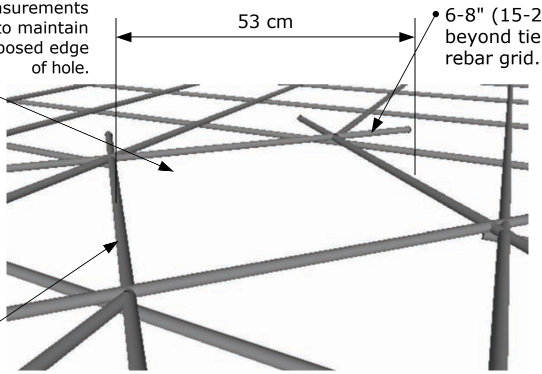
2 S107 **Steel Lintel Jamb Detail**

Scale: 1mm : 20mm



3 S107 **Roof Rebar Details**

Scale: Not to scale



4 S107 **Floor Rebar Details**

Scale: Not to scale

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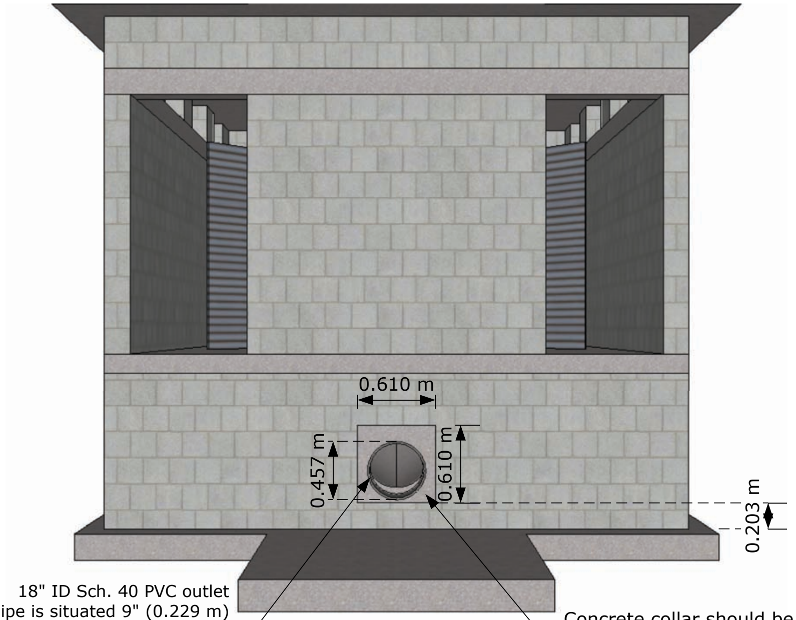
Sections & Details

S.107



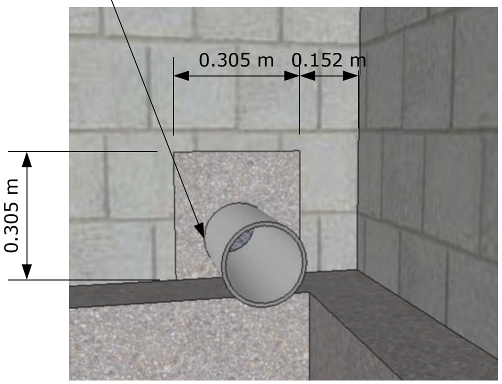
18" ID Sch. 40 PVC outlet pipe is situated 9" (0.229 m) from floor (foundation) and is encased by 24" Wide x 24" Tall x 8" Deep (0.610m x 0.610m x 0.203m) concrete collar.

Concrete collar should be formed. Forms should be poured with 4000psi concrete.

1 S108 **18" Effluent Pipe Notes**

Scale: Not to scale

Bottom of 6" (0.152 m) SDR or Sch. 40 PVC outlet pipe is situated 1" (2.54cm) from floor.



2 S108 **6" Effluent Pipe Details**

Scale: Not to scale

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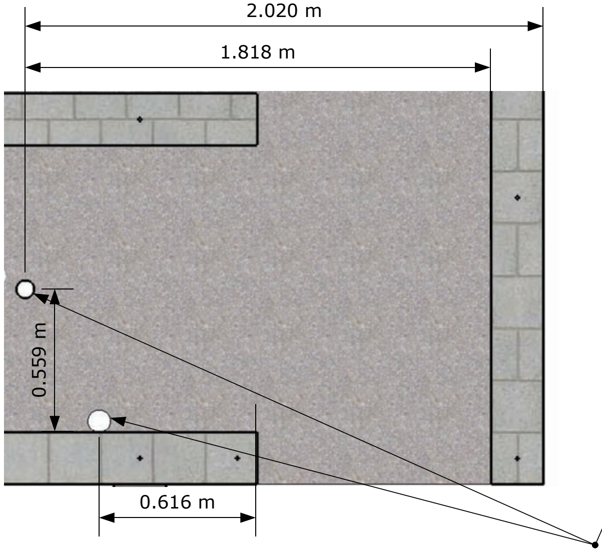
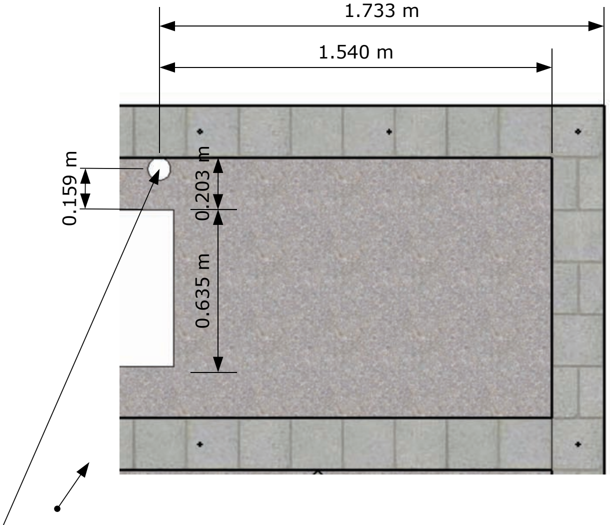
Effluent Piping Details
S.108





3.5" (8.89cm) diameter hole for
3" Schd.40 DWV vent

1
S109
Vent Hole Location Detail
Scale: 1mm : 20mm

2
S109
Vent Hole Location Detail
Scale: 1mm : 20mm

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Vent Location Details
S.109

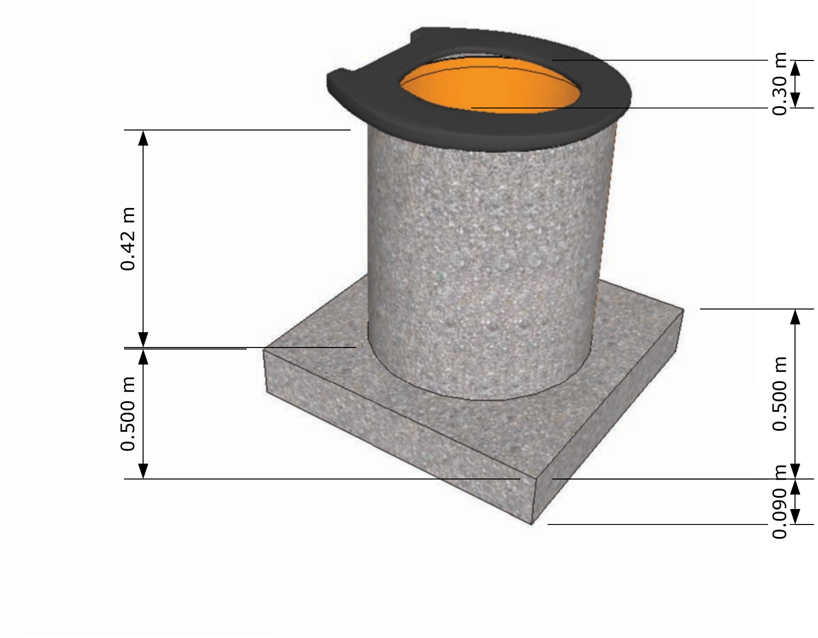
EcoSan Toilet

- Toilet is constructed from a standard toilet seat, a 20L bucket, and mortar poured around exterior.

- Pedestal is constructed from poured concrete and standard wooden forms

- Toilet is bonded to pedestal by placing the mortared bucket and toilet seat inside formwork before the final concrete pour

For fabrication instructions, see APPX 1.



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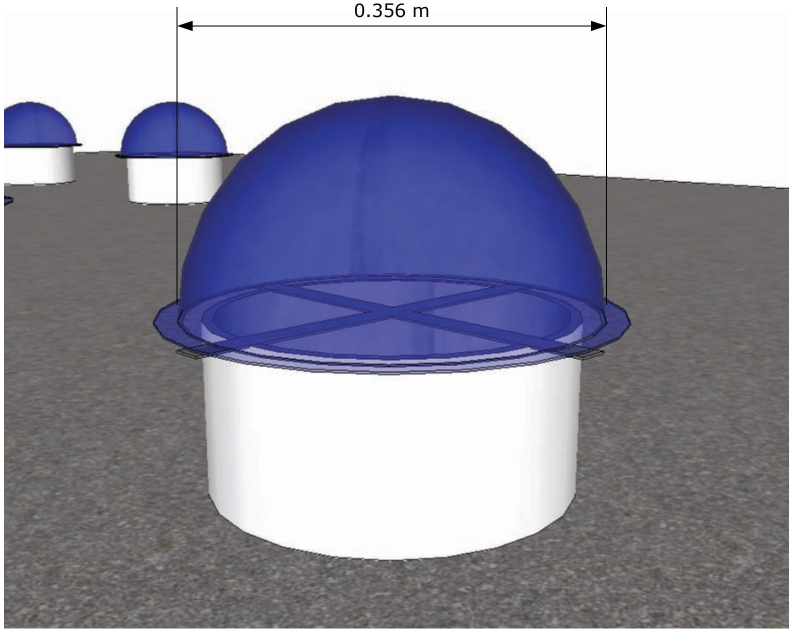
EcoSan Toilet
S.110

Lexan Dome:
http://www.globalplastics.ca/domes.htm



Skylights

- 14.25" (0.3620 m) Lexan domes, 3/16" (0.0048 m) thick.

- Mounts are 1" wide x 16.25" long x 1/2" thick (0.0254m x 0.413m x 0.0127m) Lexan cross-stays resting on accommodating groves in PVC pipe.

- Vent pipes are 12" (0.914 m) sections of 12" Sch. 40 PVC, secured 6" into roof pad and extending 6" above it.

- Mounts are affixed to 12" PVC pipe via two, 1" (2.54cm) #6 stainless steel (18-8) machine screws at each point of contact.

- Lexan dome is solvent bonded to accommodating 3/16" (0.0048") groove in Lexan mounts.

- Risers may be perforated with 9.5mm holes in upper 7.6cm to provide added ventilation.

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Skylight Design & Details
S.111

1.1 DESIGN LOADS

A. THE STRUCTURE WAS DESIGNED FOR THE LIVE LOADS SHOWN BELOW AND DEAD LOADS AS REQUIRED BY CONSTRUCTION IN ACCORDANCE WITH IBC 2006. LOADS DUE TO SNOW LOAD BUILD UP WERE CONSIDERED IN DESIGN OF STRUCTURAL COMPONENTS ADJACENT TO PARAPETS, HIGH BUILDING WALLS, ETC. INCREASE IN THESE LOADINGS, DUE TO CHANGE IN FUNCTION, CONSTRUCTION MATERIALS, ETC. SHOULD NOT BE CHANGED WITHOUT APPROVAL FROM THE RESPONSIBLE STRUCTURAL ENGINEER.

B. THE BASIC STABILITY OF THE STRUCTURE IS DEPENDENT UPON THE DIAPHRAGM ACTION OF FLOORS, WALLS & ROOF ACTING TOGETHER. PROVIDE GUYS, BRACES, STRUTS, ETC. TO ACCOMMODATE LIVE, DEAD AND WIND LOADS UNTIL FINAL CONNECTIONS BETWEEN THESE ELEMENTS ARE MADE.

C. MECHANICAL UNITS WITH WEIGHTS SHOWN IN PLAN AND SUPPORTED BY THE STRUCTURE WERE CONSIDERED IN THE DESIGN OF THE STRUCTURE. ADDITIONAL MECHANICAL EQUIPMENT NOT SHOWN ON STRUCTURAL DRAWINGS AND HAVING A WEIGHT IN EXCESS OF 400 POUNDS SHALL BE BROUGHT TO THE ATTENTION OF THE STRUCTURAL ENGINEER PRIOR TO INSTALLATION.

D. LIVE LOADS SHOWN BELOW ARE IN POUNDS PER SQUARE FOOT.

ROOF LIVE LOAD: 0.97kip/2.6psf
FLOOR LIVE LOAD: 30kip/100psf
SEISMIC PEAK GROUND ACCELERATION: 32.17ft/sec2
SEISMIC BASE SHEAR: 67.09 kip/363.24psf
BASIC WIND SPEED: 120mph

1.2 SHORING

A. PROVIDE SHORING AS REQUIRED TO MAINTAIN STABILITY OF THE STRUCTURE, ADJACENT UTILITIES, CONSTRUCTION, AND EMBANKMENTS DURING THE CONSTRUCTION PERIOD. STRENGTH AND PLACEMENT OF SHORING IS TOTALLY THE RESPONSIBILITY OF THE CONTRACTOR.

B. REMOVE FINISHES, SUCH AS PLASTER, STUCCO, ETC. SO THAT SHORING WILL BE IN DIRECT CONTACT WITH STRUCTURAL MEMBERS.

C. WHERE SPACES BETWEEN SHORING AND EXISTING MEMBERS EXIST, DRIVE HARDWOOD WEDGES SNUG AND TOE NAIL TO SHORING.

1.3 EXISTING CONDITIONS

A. CONTRACTOR MUST FIELD CHECK AND VERIFY DIMENSIONS AND ELEVATIONS OF EXISTING STRUCTURES PRIOR TO BEGINNING OF CONSTRUCTION.

1.4 LOGISTICS AND PROCUREMENT

A. CONTRACTOR SHALL HAVE DETERMINED AND VERIFIED QUANTITIES, DIMENSIONS, SPECIFIED PERFORMANCE CRITERIA, INSTALLATION REQUIREMENTS, MATERIALS, CATALOG NUMBERS AND SIMILAR DATA WITH RESPECT THERETO AND REVIEWED OR COORDINATED ALL DRAWINGS TO ASSURE COMPLIANCE WITH THE REQUIREMENTS OF THE WORK AND THE CONTRACT DOCUMENTS.

1.5 FOUNDATIONS

A. A SOIL BEARING CAPACITY OF 2000 P.S.F. WAS USED FOR FOOTING DESIGN. IF SOIL OF THIS CAPACITY IS NOT ENCOUNTERED AT ELEVATIONS INDICATED, INCREASE FOOTING SIZE OR LOWER AS DIRECTED BY THE RESPONSIBLE ENGINEER.

B. EXTERIOR FOOTING BOTTOMS SHALL BE 2'-6" MINIMUM BELOW FINISH GRADE.

C. FOUNDATION WALLS ARE DEPENDENT UPON THE COMPLETED INSTALLATION OF FLOORS AND ROOFS FOR THEIR STABILITY. DO NOT PLACE BACKFILL UNTIL THESE ELEMENTS ARE COMPLETELY INSTALLED, OR PROVIDE SHORING AND BRACING.

D. COMPACT FILL AND BACKFILL TO 95% OF A.S.T.M D-698. PERFORM FILL AND BACKFILL OPERATIONS UNDER THE DIRECT SUPERVISION OF THE RESPONSIBLE ENGINEER.

E. PRIOR TO POURING CONCRETE, CONSULT THE RESPONSIBLE ENGINEER TO PERFORM TESTS, BORINGS, ETC. REQUIRED TO CERTIFY THAT THE SOIL BEARING CAPACITY MEETS OR EXCEEDS THAT SHOWN IN THE GENERAL NOTES ABOVE. ENGINEER SHALL VERIFY SUBGRADE CAPACITIES PRIOR TO INSTALLATION OF DRAINAGE FILL AND MOISTURE BARRIER.

1.6 MASONRY

A. MANUFACTURE AND INSTALL MASONRY IN ACCORDANCE WITH (ACI 530/ASCE 5/TMS 402),(ACI 530.1/ASCE 6/TMS 602). BLOCK: CONCRETE MASONRY UNITS: 1,900 PSI COMPRESSIVE STRENGTH (AVERAGE OF THREE UNITS). DESIGNED F'M: 1500 PSI. A.S.T.M. C-90 WITH MINIMUM DENSITY OF 125 LBS. PER CU. FT. FOR NORMAL WEIGHT AND 100 LBS. PER CU. FT. FOR LIGHT WEIGHT UNITS.

B. BLOCK USED IN EXTERIOR WALLS, INTERIOR BEARING WALLS AND WALLS WITH VERTICAL STEEL REINFORCING SHALL BE MANUFACTURED AND LAID SUCH THAT WEBS ARE IN COMPLETE ALIGNMENT.

C. MORTAR: A.S.T.M. C-270 TYPE S.

D. GROUT: A.S.T.M. C-476 (NON SHRINK, NON METALLIC).

E. REINFORCING: A.S.T.M. A-615, GRADE 60.

F. BLOCK SHALL HAVE GALVANIZED LADDER TYPE HORIZONTAL JOINT REINFORCING AT 16" O/C MAXIMUM WITH PREFABRICATED CORNER AND "T" PIECES UNLESS NOTED. PROVIDE AN ADDITIONAL ROW ABOVE AND BELOW OPENINGS AND EXTEND 2'-0" BEYOND JAMBS.

G. HORIZONTAL JOINT REINFORCING SHALL BE IN ACCORDANCE WITH ASTM - A951 AND SHALL BE MANUFACTURED FROM 8 GAGE (0.148) MIN. COLD DRAWN STEEL WIRE CONFORMING TO ASTM A-82. IT SHALL CONSIST OF TWO DEFORMED LONGITUDINAL SIDE RODS WELDED AT 16" (40.6cm) INTERVALS TO A PERPENDICULAR CROSS ROD FORMING A LADDER DESIGN. CROSS ROD AND SIDE RODS SHALL BE LOCATED IN THE SAME PLANE AS THE LONGITUDINAL RODS. OUT TO OUT SPACING OF SIDE RODS SHALL BE APPROXIMATELY 2" LESS THAN THE NOMINAL WALL THICKNESS. JOINT REINFORCEMENT SHALL INSTALLED EVERY TWO COURSES.

H. JOINT REINFORCEMENT IN EXTERIOR WALLS TO BE HOT DIPPED GALVANIZED, AFTER FABRICATION, IN ACCORDANCE WITH ASTM A-153 CLASS B2 (1.80 OZ./SQ. FT.).

I. CONTINUOUS BEARING COURSE SHALL BE 8" DEEP, ASTM C-90 KNOCK-OUT BOND BEAM BLOCK UNITS WITH CELLS FILLED SOLID WITH PEA GRAVEL CONCRETE. VERTICAL SPACING SHALL NOT EXCEED 4' -0" (1.22m).

J. FILL CELLS OF BLOCK SOLID WITH MORTAR IN ALL CELLS CONTAINING VERTICAL REINFORCMENT AND IN COURSE DIRECTLY BELOW CHANGES IN THICKNESS AND BOND.

K. BLOCK SHALL BE LAID IN FULL BED OF MORTAR INCLUDING CROSS-WEBS.

1.7 STEEL LINTEL SCHEDULE

A. PROVIDE AND INSTALL LINTELS FOR OPENINGS IN MASONRY WALLS. UTILIZE LINTEL SIZE AS INDICATED ON THE SCHEDULE BELOW.

B. #4 REINFORCING BAR (GRADE 60) IS TO BE SET APPROXIMATELY 3.8cm FROM THE TOP OF ALL LINTEL DESIGNS. TOP HORIZONTAL REINFORCEMENT IS TO BE A CONTINUOUS TIE.

C. SHORE LINTELS TO PREVENT ROTATION DURING CONSTRUCTION.

D. LINTELS TO HAVE MINIMUM 15.2cm BEARING ON SOLID MASONRY FOR EACH END, OR A MINIMUM 30.5cm DEEP COMBINED.

MARK	MATERIAL
L-1	3" (7.6cm) x 4' (1.22m) x 3/8" (0.95cm) steel angle bar tack-welded to 7-5/8"(0.194m) x 44-3/8" (1.127m) x 1/4" (0.006m) stainless steel plate (grade 304)

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General Notes
D.001

1.8 STRUCTURAL STEEL

A. FABRICATE AND ERECT STRUCTURAL STEEL IN ACCORDANCE WITH A.I.S.C. MANUAL OF STEEL CONSTRUCTION, THIRTEENTH EDITION.
B. STEEL - A.S.T.M. A36 FOR ANGLES, CHANNELS, AND MISCELLANEOUS SHAPES. - A.S.T.M. A992 (50 KSI)FOR WF SHAPES.
C. BOND BEAMS SHALL BE REINFORCED WITH 2 #4/#13 REBAR TIES SPANNING HORIZONTAL LENGTH OF STRUCTURE AND TIED INTO ALL ALIGNED VERTICAL REINFORCEMENTS.
D. COLUMN BASE ANCHOR RODS - ASTM F1554, GRADE 36.
E. HOOKED, HEADED OR THREADED ANCHOR RODS - ASTM A307, GRADE A.
F. NUTS - ASTM A563, HEAVY.
G. WASHERS - ASTM F436.
H. HIGH STRENGTH BOLTS FOR CONNECTIONS - ASTM A325 OR A490.
I. COAT STEEL EXPOSED AFTER BUILDING IS COMPLETED WITH ONE SHOP COAT OF AN APPROVED RUST INHIBITIVE PRIMER. PAINT STEEL EXPOSED TO WEATHER AFTER BUILDING IS COMPLETED WITH TWO ADDITIONAL COATS OF RUST INHIBITIVE PAINT AFTER ERECTION. PAINT SHALL BE COMPATIBLE WITH SHOP COAT.

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D.002

5.3 Low cost pedestal with plastic seat

A commercially made plastic toilet seat is required. First holes are made with a hot wire in the supporting plastic ribs under the seat, so that a ring of wire can be threaded through under the seat (Figure 5-7). The hollow under the plastic seat can then be filled with a strong 2:1 river sand and cement mix with the wire inside (Figure 5-8). At the same time a 20 litre bucket (with base sawn off) is placed over the seat in a central position (Figure 5-9) and L- shaped pieces of wire inserted around the rim of the bucket into the cement. This is left to cure for a few hours. Then the side walls of the bucket can be covered with a 2:1 sand and cement mix. This is left to harden a little. Later some thin wire is laid spirally up the side walls of the pedestal to strengthen the unit (Figure 5-10). A further layer of mortar is then applied to the side walls. This is left to cure for at least 2 days, being kept wet at all times. The pedestal is then carefully overturned into a base mould made of wood (Figure 5-11), and the base made with more strong concrete - and left to cure again. This procedure makes a neat, comfortable and long lasting pedestal (Figure 5-12).

Figure 5-7: Ring of wire added to plastic toilet seat

Figure 5-8: Plastic toilet seat filled with strong concrete

Figure 5-9: Plastic bucket placed over toilet seat

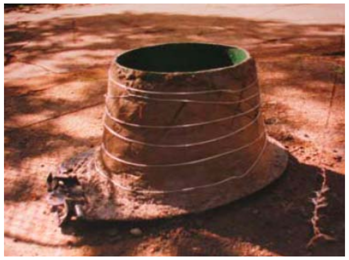

Figure 5-10: Concrete reinforcement added around first layer of concrete

Figure 5-11: Completed pedestal placed in wooden mold

Figure 5-12: Completed low cost pedestal with plastic seat

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APPX 1

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