Phase II Bioenergy Production from MSW by High Solids Anaerobic Digestion

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April 1, 2017-July 2, 2017

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LIST OF ACRONYMS AND ABBREVIATIONS

AD	Anaerobic Digestion
B	Biosolids
BMP	Biochemical Methane Potential
$CaCO_3$	Calcium Carbonate
CH_4	Methane
C&T	Collection and Transportation
CHP	Combined Heat and Power
d	day
FW	Food Waste
GHG	Greenhouse Gases
GW	Green Waste (also known as yard waste)
HS-AD	High Solids Anaerobic Digestion
I	Sensitivity Index
L	Limestone
L-AD	Liquid Anaerobic Digestion
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
LCCA	Life Cycle Cost Analysis
LCI	Life Cycle Inventory
MSW	Municipal Solid Waste
NH_4^+	Ammonium
O&M	Operations and Maintenance
OFMSW	Organic Fraction of Municipal Solid Waste
OS	Oyster Shells
PV	Present Value
S/I	Substrate to Inoculum Ratio
SS	Seed Sludge
SS-AD	Solid State Anaerobic Digestion
STP	Standard Temperature and Pressure
TS	Total Solids
UPV	Uniform Prevent Value Factor
UPV*	Non-Uniform Present Value Factor
VFA	Volatile Fatty Acids
VS	Volatile Solids
WAS	Waste Activated Sludge
WtE	Water to Energy

QUARTERLY REPORT #2

PROJECT TITLE: Phase II Bioenergy Production from MSW by High Solids Anaerobic Digestion

PERFORMANCE PERIOD: April 1, 2017-July 2, 2017

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INTRODUCTION AND OBJECTIVES

Energy recovery from municipal solid waste (MSW) is commonly practiced in the US by collecting and utilizing landfill gas for heat, vehicle fuel or conversion to electricity using internal combustion engines or turbines. The most common strategy in the US for enhancing landfill gas production is through recirculation of leachate through the entire waste stream. Many landfills in Europe; however, separate the organic fraction of MSW (OFMSW) for energy recovery through anaerobic digestion (AD). This promotes faster OFMSW degradation, a higher biogas quality based on methane (CH_4) composition, lower fugitive greenhouse gas (GHG) emissions and production of a nutrient rich compost (also called digestate) that can be used as a fertilizer. Depending on the total solids (TS) concentration of the substrate, anaerobic digestion can be applied under wet (≤ 10% TS), semi-dry (11-19% TS) or high solids (≥20%TS) conditions. Advantages of High Solids AD (HS-AD; also known as solid-state AD [SS-AD] or dry fermentation) include lower parasitic energy losses, reduced water use and leachate production and recovery of nutrients as a compost product.

The overall goal of this project is to improve the environmental and economic sustainability of HS-AD of OFMSW in Florida. Specific objectives for Phase II (Fig. 1) are to:

1. Investigate the performance of HS-AD of OFMSW with varying substrate ratios (green waste [GW], food waste [FW], biosolids) and temperatures (35, 55 °C).
2. Apply life cycle analysis (LCA) to guide the selection of waste sources and operating conditions for HS-AD and
3. Compare HS-AD with other waste management options (e.g., landfilling, waste to energy (WTE), composting) to ensure economic and environmental sustainability.

WORK ACCOMPLISHED DURING THIS REPORTING PERIOD

Objective 1: Investigate HS-AD performance with varying substrate and temperatures

The results of the first bench-scale experiment were described in the first quarterly report. Briefly, the goal of the experiment done for the first quarterly report was to quantify the effects of biosolids addition in HS-AD of FW+GW. Some challenges were encountered during that study and the results were inconclusive. Thus, the bench-scale studies for HS-AD with the addition of biosolids were repeated.

Experimental set up: Biochemical Methane Potential (BMP) Assays were set up as described in Hinds et al. (2016). Different mixtures (including FW+GW and FW+GW+B) were used to test the effects of biosolids (B) on the performance of HS-AD of FW and GW (Figure 1). Crushed oyster shells were added to provide an alkalinity of 3,000 mg/L (as Calcium Carbonate ($CaCO_3$)). Each digestion set consisted of eleven reactors (feedstock as initial (2), intermediates (6), and digestate as final (3)), while the nine blank digesters (with only inoculum) were prepared to correct for CH_4 yields from the inoculum (feedstock as initial (2), intermediates (4), and digestate as final (3)). Digesters were run in 250-ml serum bottles at a constant mesophilic temperature of 35°C. TS content was set at 20% and the S/I ratio was set at 2.7 on a Volatile Solid (VS) basis.

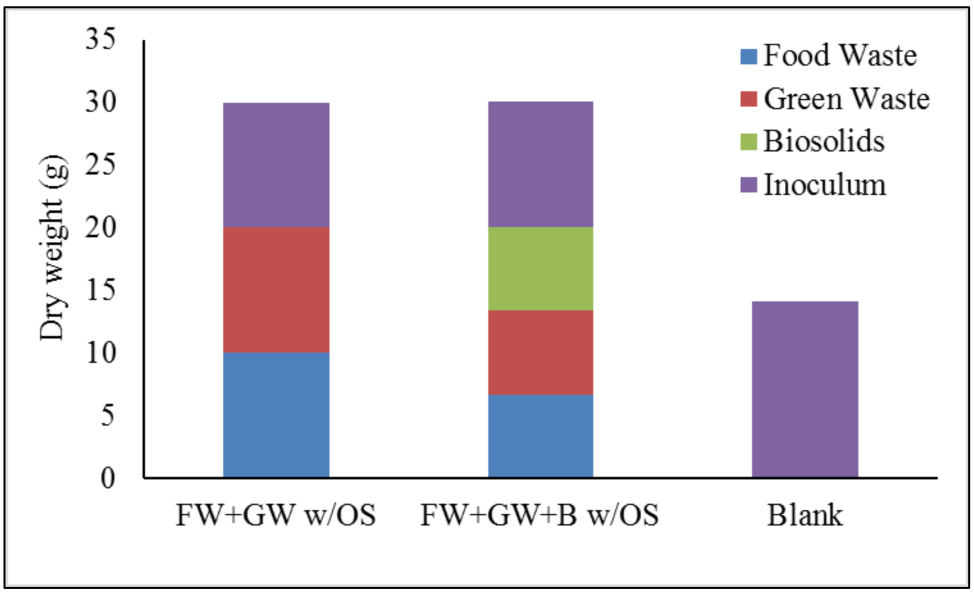

Figure 1. Digester compositions.

The inoculum was dewatered anaerobically digested sludge from the Northeast Clearwater Treatment Facility (Clearwater, Florida). FW waste was synthetically prepared based on an average compositional analysis of FW in literature (Table 1) and consisted of: apples, banana peels, oranges, carrots, beef, chicken, bread, cheese pasta, and rice. GW was based on the typical composition of GW in Florida and contained: oak tree leaves, pine needles, grass, and shrubbery cuttings. Biosolids consisted of dewatered (via screw press) waste activated sludge (WAS) from the Falkenburg Advanced Wastewater Treatment Plant (Tampa, FL). In these experiments, biogas and CH_4 content of the biogas were measured. Also, the following chemical parameters of the leachate were analyzed: pH, alkalinity, Volatile Fatty Acid (VFA), soluble Chemical Oxygen

Demand (sCOD), Total Nitrogen (TN), ammonium (NH_4^+-N), TS, and VS. These analytical methods were described in the first quarterly report.

Table 1. Composition of synthetic FW used for the experiment.

% Wet weight fraction	MTT Agrifood Research Finland (2010)	Rajagopal et al., (2017)[1]	This study
Fruits/vegetables	78.6	68.3	72.8
Meat	8.2	9.2	8.8
Dairy products	1.9	8.1	5.5
Bread and bakery	6.4	6.8	6.6
Pasta/rice	4.9	7.6	6.4
Total	100	100	100

[1]: Juice and sugar starch were considered as a miscellaneous portion, and the miscellaneous portion was excluded.

BMP Assay Results: Figure 2(a) and 2(b) show the results of the cumulative biogas production and CH_4 content in biogas respectively. As shown in Figure 2(a), biogas production from FW+GW+B was significantly higher than that of the digesters with FW+GW. However, the low CH_4 contents in biogas were observed over 14 days for FW+GW and FW+GW+B compared to the blank (Figure 2(b)). The low methane content in the biogas may have been caused by imbalances in chemistry that affect the anaerobic bacterial community (Brown & Li, 2013). The imbalance resulted in accumulation of VFAs, which caused a dramatic drop in pH (Table 2). VFA concentrations of 17,914 mg/L and 15,612 mg/L were found in the digesters with FW+GW and FW+GW+B, respectively. According to Khanal (2011), VFA concentrations inhibitory to methanogenesis can be observed at >10,000 mg/L. Thus, both digestion sets were above the inhibitory concentration resulting in inhibition of methanogen activity and low CH_4 production.

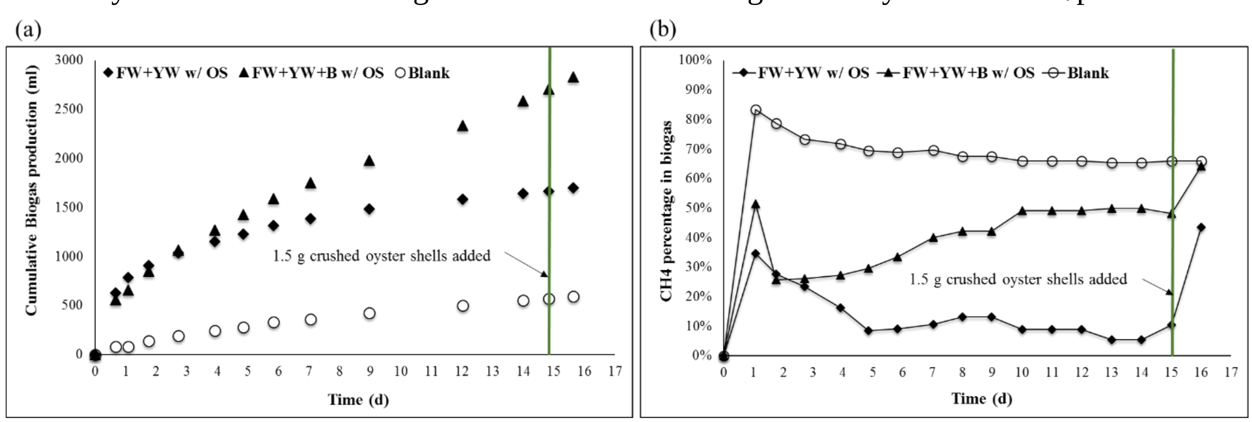

Figure 2. Biogas production of the HS-AD: (a) cumulative biogas production and (b) CH4 content in biogas.

A comparison of CH_4 yields for FW+GW with and without biosolids is shown in Figure 3. Due to higher biogas and CH_4 content in biogas for FW+GW+B, CH_4 yields for FW+GW+B was higher than FW+GW. The average methane yields for 16 days were 5.5 and 41.2 mL CH_4/g VS for digesters without and with biosolids addition, respectively. The results indicate that biosolids can improve the CH_4 yield for HS-AD of FW+GW. The biosolids addition in the HS-AD increased the alkalinity concentration in the digesters (Table 2), and this increment may result in the increased CH_4 production. These sets of experiments have added crushed oyster shells (3g/L) as an alkalinity source, which helped to increase the alkalinity concentrations in the digesters, but their buffer capacity was not enough to maintain the neutral pH (Table 2). Additional oyster shells (1.5 g) were added to the digesters on day 15, resulting in improvement of CH_4 content in biogas (Figure 2(b)). During the digestion, the digestion sets with FW+GW+B had a higher NH_4^+-N concentration than those of the digestion sets with FW+GW (Table 2). However, NH_4^+-N concentrations for both digesters were not found to be in the toxic range (1,500-1,700 mg/L) (Gerardi, 2003). This is due to the higher nitrogen content of the WAS compared with FW+GW.

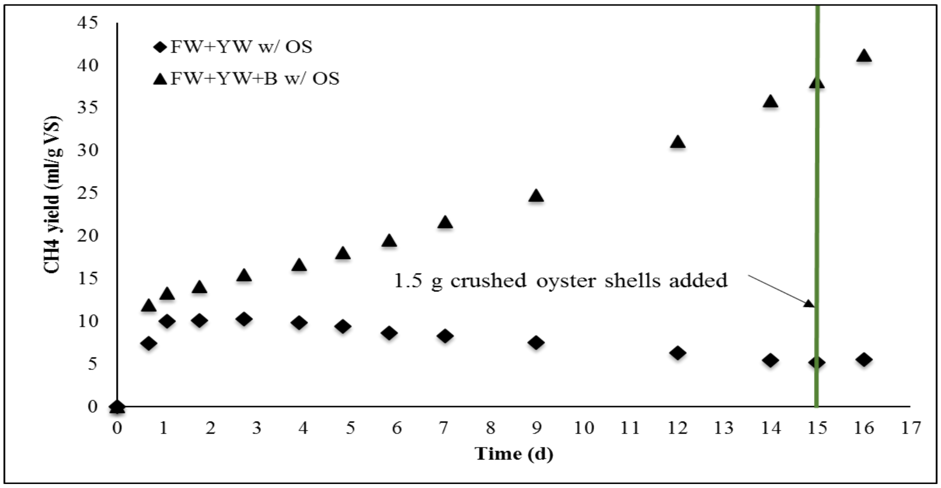

Figure 3. CH_4 yields for HS-AD.

Table 2. Results of chemical analysis.

Item	FW+GW w/OS		FW+GW+B w/ OS		Blank (Inoculum only)	
	Day 0	Day 14	Day 0	Day 14	Day 0	Day 14
TS (g/g)	0.20±0.005	0.18±0.006	0.20±0.004	0.18±0.003	0.14±0.002	0.13±0.001
VS (g/g)	0.17±0.007	0.15±0.013	0.17±0.004	0.13±0.007	0.10±0.001	0.09±0.005
pH	6.99±0	5.13±0.02	6.95±0.01	5.69±0.04	8.08±0.01	8.20±0.02
VFA (mg/L)_	1,722±359	17,914±1,583	3,449±112	15,612±787	300±29	393±15
Alkalinity (mg $CaCO_3$/L)	330±4	560±44	338±11	966±65	291±24	1,252±127
sCOD (mg/L)	23,834±832	59,562±3,123	46,017±1,298	46,137±2,015	1,903±245	2,015±50
TN (mg/L)	904±15	2,216±76	1,097±31	2,705±156	575±40	781±37
NH_4^+-N(mg/L)	407±4	1,323±40	423±7	1,987±21	471±28	697±48

Objective 2: Apply life cycle assessment (LCA) to guide the selection of waste sources and operating conditions for HS-AD

To perform environmental LCA of HS-AD, a Life Cycle Inventory (LCI) analysis was carried out. Since there is no HS-AD system in Hillsborough County, FL, LCI was constructed based on a hypothetical system. The system configuration of HS-AD was based on batch single-stage technologies from two companies: BioFerm's Dry Fermentation technology and Zero Waste Energy's (ZWE) SMARTFERM technology. Both technologies consist of concrete-based digesters with steel gas-tight doors, a percolation tank, a biogas storage system, a biofilter, and a combined heat and power (CHP) unit. The difference between the two technologies results mainly from the location of percolate tanks, gas storage system, and operation temperature: ZWE uses belowground percolate tanks (ZWE, 2015), while BioFerm employs ground-level percolate tanks (BioFerm, n.d.). For the gas storage system, ZWE employs a double-membrane roof-mounted bladder (ZWE, 2015), while BioFerm uses a flexible gas storage bag (BioFerm, n.d). ZWE operates at thermophilic conditions (ZWE, 2015), while BioFerm operates at mesophilic ones (BioFerm, n.d.).

The main data sources reviewed included company websites and product descriptions, case studies of current plants, and batch anaerobic digesters bench-scale studies (BASF, 2014; BING, 2006; CWMI, 1990; EEA Mass, n.d.; Engineering Toolbox a, b & c, n.d.; Goodfellow, n.d.; IFR& FCS, n.d.; Ma et al., 2011; Petric & Selimbašic, 2008; Scano et al., 2014; Sliusar & Armisheva, 2013; Smith & Krüger Inc., 2009; US EPA, 1994 & 2016; Zhang et al., 2009). To calculate the materials and energy requirements of HS-AD, an Excel-based program was developed based on inputs including waste compositions, digester dimensions, percent occupation (based on stackable height), annual capacity, retention time, temperature specifications (operation temperature, ambient temperature, soil temperature). Fixed parameters in the program (Table 3) include the density and heat capacity of waste materials and thermal conductivity of the digester components (concrete, steel, polyurethane foam). Through literature review, materials for each components of HS-AD were identified, shown in Table 4.

Table 3. Physical properties of waste materials and components of the digester.

Physical property	Value	Reference(s)	Note
Density of food waste (kg/m^3)	447.24	EPA, 2016	Averaged values from several sources;
Density of yard waste (kg/m^3)	311.47	CWMI, 1990	Average density of shredded yard waste;
Density of Biosolids (kg/m^3)	400.46	Smith & Krüger Inc., 2009	Density of dried biosolids
Density of concrete (kg/m^3)	2400	Engineering Toolbox a, n.d.	--
Density of galvanized steel (kg/m^3)	7830	Repairing Engineering, 2016; AGA, 2017	Density of steel; Galvanization did not change properties of steel

Table 3. (Continued)

Physical property	**Value**	**Reference**	**Note**
Density of solid polyurethane foam (kg/m^3)	100	BASF, 2014; BING, 2006	--
Specific heat capacity of food waste (kJ/kg*°C)	1.65	EEA Mass, n.d; IFR& FCS, n.d.; Petric & Selimbašic, 2008; Scano et al., 2014; Sliusar & Armisheva, 2013	Averaged values from different studies; 75% moisture content
Specific heat capacity of yard waste (kJ/kg*°C)	1.36	EEA Mass, n.d.; EPA , 1994; Sliusar & Armisheva, 2013	50% moisture content
Specific heat capacity of biosolids (kJ/kg*°C)	0.9	Zhang et al., 2009	Used heat capacity of dry wastewater treatment sludge.
Thermal conductivity of concrete (W/m*°C)	1.52	Engineering Toolbox b, n.d	Thermal conductivity of dense concrete
Thermal conductivity of steel (W/m*°C)	24.3	Engineering Toolbox c, n.d	-
Thermal conductivity of solid polyurethane foam (W/m*°C)	0.025	BASF, 2014; BING, 2006	-

Table 4. List of components of HS-AD plant and possible materials.

Component	**Material**	**Reference**
Loading/preparation area	Masonry/concrete structure	Persson et al., 1979; ZWE, 2015
Digester (s)	Masonry/concrete structure	BioFerm, n.d.;Persson et al., 1979; ZWE, 2015
	Steel structure	ZWE, 2015
Heating System	Steel wires	Persson et al., 1979
	Water/steam Heat Exchanger	SusCon, n.d.
	Electrical Systems	BioFerm, n.d.; ZWE, 2015
Mixing/Agitation System	Mechanical System (Pump or Impellers)	ERC, 2012
	Gas Bubbling	
Percolate Tank	Steel	BioFerm, n.d.

Table 4. (Continued)

Component	Material	Reference
Piping System	Percolate Recirculation System (PVC or HDPE)	OCW MIT, 2004; System group, 2012;
	Biogas Collection System (PVC or galvanized steel)	Energypedia, 2015; Walsh et al., 1988
	Aeration System (PVC or thermoplastic materials; metal - black iron, stainless steel, copper, or aluminum)	EDI, 2011; EXAIR Corporation, 2016
	Exhaust Gas System (PVC, CPVC, Polypropylene, or stainless steel)	DuraVent Inc., n.d.
Pumping System	Percolate Recirculation Pump (peristaltic pump)	Degueurce et al., 2016; Rico et al., 2015
	Compressors (for aeration, exhaust air, and biogas collection systems) (stainless steel Liquid Ring Compressor).	Claro Inc., 2009; Sterling SIHI Inc., 2017.
Biogas Storage System	Flexible storage bag	BioFerm, n.d.
	Roof-mounted double-membrane bladder	ZWE, 2015
Sludge Removal Mechanism	Sludge Auger	Persson et al., 1979
	Mechanical removal using front loader.	BioFerm, n.d.; Koenig, 2011; ZWE, 2015
Drainage Grates	Galvanized steel, cast iron, brass, or PVC.	NDS Inc., 2017
Biofilter	Bulk Media Filters (closed chamber containing single or multiple layers of biofilter media, typically soil, compost, peat, wood chips, or a mixture of these).	Anit & Artuz, n.d.; N.E.M Business Solutions, 2002
Compressed-air Storage Vessel	Fiberglass, Carbon fiber, Kevlar/Aramid fiber	Amalga Composites Inc., n.d.
Gas-tight door	Galvanized steel sheets, solid polyurethane filling.	BG Doors International Inc., 2014; Heiden Systems, 2016.

Since the LCA was based on a hypothetical system, several assumptions were made to estimate material and energy requirements for HS-AD. Assumptions regarding the design of the HS-AD plant were the following: only concrete digesters were considered, because steel digesters are not ideal for large-scale digestion system (ZWE, 2015). The ratio of steel to concrete for the concrete structure was assumed to be 110 kg of steel/m^3 of concrete (ProActive Inc., n.d.). It was assumed that no insulating material would be used. Assumptions for the masonry of the concrete digesters were that the footing and walls would be 20 cm thick, and the ceiling of 10 cm thick. For the footing, it was assumed that the soil had a high load bearing capacity (load-bearing value in the range of 3,500 - 4,000 psi) (Beall, 2001), and thus direct foundation on the subsoil was considered (Beall, 2001). Percolate recirculation was assumed to occur every two hours, totaling 12 times a day and at a ratio of 0.75 L of percolate/kg of waste (Rico et al., 2015). Short and frequent recirculation periods were chosen because such practice was found to improve the stability and speed of the digestion for a batch digester operating under thermophilic conditions (Rico et al., 2015).

It was assumed that the heating of HS-AD is accomplished through the CHP unit. For the determination of the heat requirements, the following assumptions were made: the average annual temperature was assumed to be that of the city of Tampa, which is 73.4 °F, and the maximum and minimum values were 81.7 °F and 65.1 °F, respectively (FCC, 2010). The average soil temperature at a depth of 2 inches was calculated to be 72.6 °F (data from Sellers Lake municipality, the closest city to Tampa with data available), by averaging the values over October 2016 to July 2017 (NWCC, 2017). It was also assumed that the interior temperature of the digesters would be 20 °C (68 °F). The total heating requirement ($E_{req.}$) to run the digesters was calculated as the summation of the heat necessary to heat the waste material to the operating temperature (E_{heat}) and the heat losses (E_{loss}) (Eq. 1). The energy required to heat the waste material was calculated by using Eq. 2. The heat loss can be separated into the heat lost by the digesters and the heat lost by the percolate tank, and the heat losses were calculated based on Eq. 3 (Salter & Banks, 2008). The heat lost to the surroundings could be calculated based on the thermal conductivities (Eq. 4) of the materials in the digester's walls and doors, the area of heat loss, and the length of heat travel through the materials (Salter & Banks, 2008). For the gas-tight door that is composed of two sheets of steel with a polyurethane filling in between, it was assumed that the heat transferred across all three layers of material would be the same.

$$E_{req.} = E_{Heat} + E_{loss} \qquad \text{(Eq.1)}$$

$$E_{heat} = [(C_{FW} \times x_{FW}) + (C_{YW} \times x_{YW}) + (C_B \times x_B)] \times \left(T_{digest} - T_{idle}\right) \qquad \text{(Eq.2)}$$

$$E_{loss} = U \times A \times (T_{out} - T_{digest}) \qquad \text{(Eq.3)}$$

$$U = \frac{1}{\sum_{i=1}^{n} \frac{l_i}{k_i}} \qquad \text{(Eq.4)}$$

Where, E_{heat} is the energy requirement to heat the waste material in kJ/kg; C_{FW} is the specific heat capacity of food waste in kJ/(kg K); C_{YW} is the specific heat capacity of yard waste in kJ/(kg K); C_B is the specific heat capacity of biosolids in kJ/(kg K); x_{FW} is the mass fraction of food waste in kg FW/kg total; x_{YW} is the mass fraction of yard waste in kg GW/kg total; x_B is the mass fraction of biosolids in kg B/kg total; T_{digest} is the operational temperature of the digester in °C; T_{idle} is the digester temperature when it is not operating in °C; U is the coefficient of heat transfer in W/(m^2 K); A is the area through which the heat transfer occurs in m^2; T_{out} is the temperature on the outside of the digester in °C; l_i is the thickness of the surface through which heat transfers in m; k_i is the conductivity of each layer of the surface in W/(m K); and n is the number of layers arranged in series. The term T_{out} varied according to the surface through which heat was being lost. For instance, T_{out} would be the soil's surface when considering the floor, the ambient temperature when considering the external walls, and the building's interior temperature when considering the internal walls. For simplicity, it was considered that all reactors would be operating at the same time, so there would be no heat transfer between the walls separating adjacent digesters. In reality, digesters are usually operated in parallel with different start up times, so that the production of biogas is constant (Degueurce et al., 2016).

Figure 4 shows an example of the input interface for the BioFerm's HS-AD system. Similar inputs are used to calculate the amount of steel, polyurethane foam, and the energy requirements. The outputs from the Excel program include: number of digesters required, mass of concrete needed (kg) per mass of waste digested (kg), mass of steel needed (kg) per mass of waste, and energy requirement per mass of waste. The mass of polyurethane foam was also calculated, but it was negligible. It is important to notice that the input of concrete and steel is a one-time event, related to the construction of the digesters, while the energy requirement is recurring. A sample output table from the Excel program is shown in Figure 5.

(a)

Concrete Requirement		
Digester's Dimensions		
Length	30	m
Width	7	m
Height	5	m
Total Internal Volume	1050	m^3
Percent Occupation	75	%
Stackable Volume	787.50	m^3
Annual Capacity	36,287.40	Metric Ton
Retention Time	28	days
Annual Operation Cycles	13	cycles

(b)

Waste Composition	**Percent Composition (w/w)**		**Density**		**Mass Waste Component**	
Food waste	33.3	%	447.24	kg/m^3	12,083.70	Metric Ton
Yard Waste	33.3	%	311.47	kg/m^3	12,083.70	Metric Ton
Biosolid	33.4	%	400.46	kg/m^3	12,119.99	Metric Ton
Annual Volume Waste Digested	93,910.50	m^3	**Average Density**	kg/m^3	**Total Mass Check**	
Volume Waste Digested per Cylce	7,223.88	m^3	386.40	kg/m^3	36,287.40	Metric Ton

Figure 4. Input values based on digester's dimensions and specifications (a), and waste composition (b) (Note: The cells in orange are the input cells).

Summary Table		
Digester	**Quantity**	
Number of Digesters	10	Units
Material		
Concrete	0.0885	kg/kg
Steel	0.0041	kg/kg
Energy		
Digester's Energy Requirement	42.81	kJ/kg
Digester's Heat Losses	770.69	kJ/kg
Percolate Tank's Heat Losses		
Pumping Energy Requirement		
Total Energy	813.51	kJ/kg

Figure 5. Sample output for the Excel program (Note: This output is for BioFerm's dry digester specified by the inputs in Figure 4).

Future work includes completing the LCI for HS-AD of a waste mixture containing food and yard wastes, and biosolids, by including the material requirements from the remaining components, such as pipes, pumps and compressors, percolate tank, biofilter, and biogas collection system and additional energy losses. Once the LCI is complete, it will be used in conjunction with existing inventory databases, such as Ecoinvent and the US LCI database (from SimaPro8) to perform a LCA of the HS-AD process, considering its specifications. The LCA results will be updated in next quarterly report.

Objective 3: Compare HS-AD with other waste management options (e.g., landfilling, waste to energy (WtE), composting) to ensure economic and environmental sustainability

Economic analysis: Life Cycle Cost Analysis (LCCA) for HS-AD with other waste management options (e.g. landfilling, waste to energy (WtE), and composting) were conducted using the present value (PV) method. The LCCA included infrastructure, operation and maintenance (O&M), collection and transportation (C&T) costs, and revenues from beneficial products including electricity, heat, and digestate. The life cycle cost (LCC) was computed as follows:

$$LCC = C_I + (C_{O\&M} \times UPV^*) + (C_{C\&T} \times UPV) - (C_{R,t} \times UPV) - (C_{R,h} \times UPV) - (C_{R,d\&c} \times UPV) - (C_{R,e} \times UPV^*) \quad \text{(Eq. 5)}$$

where C_I is the initial cost, $C_{O\&M}$ is the O&M cost, $C_{C\&T}$ is the C&T cost, $C_{R,t}$ is the revenues from tipping fee saving, $C_{R,h}$ is the revenues from heat sales, $C_{R,d\&c}$ is the revenues from digestate or compost, and $C_{R,e}$ is the revenue from electricity sale. The UPV is a uniform present value factor, and UPV* is a non-uniform present value factor. The discount or interest rate and the escalation rate used to calculate UPV and UPV* were assumed to be 1.9% (the average rate for 10 years) and 0.65%, respectively (EERC, 2017; USIR, 2017).

The available amounts of the wastes were estimated based on the past waste production from Hillsborough County, Florida (Figure 6). Residential FW was not considered in this analysis because there is no separated collection system for residential FW in Hillsborough County. Based on the past FW, GW and B productions from Hillsborough County, it was assumed that 20% of the commercial FW, 4% of the GW, and 58% of biosolids (total amount: approximately 55,068 wet tonnes/yr) could be used as feedstock for HS-AD. The C&T cost for the wastes was \$0.1/mile/ton, which was based on Faucette *et al.* (2002). Transportation vehicles were assumed to have a haul loading of 30-tonnes, with an average travel distance of 50-miles round trip (Faucette et al. 2002). For all options, the land acquisition was not considered in this analysis.

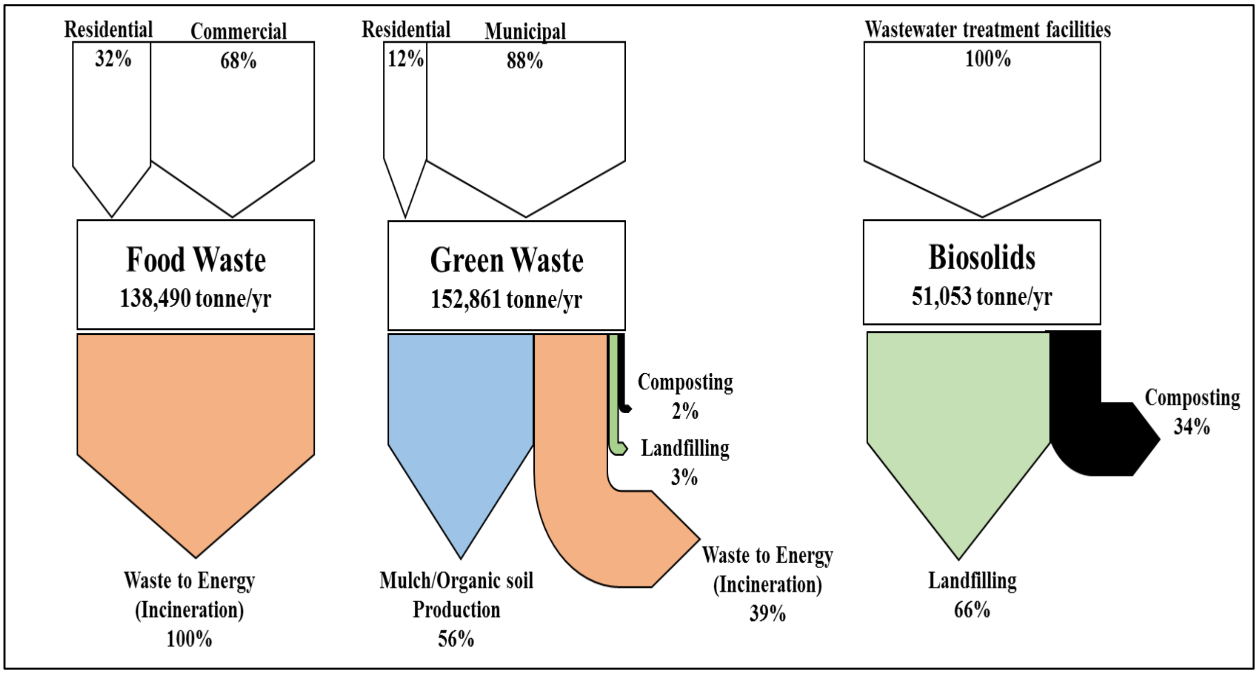

Figure 6. Production and management flow diagram of FW, GW, and biosolids in 2015.

The HS-AD system was assumed to have the same configuration as a BIOFerm Dry Fermentation system, which was described in the first quarterly report. The operating condition for the HS-AD system was assumed to be the same as the experimental conditions (a waste mixture ratio of FW, GW, and biosolids was 1:1:1 by TS) with a 28-day retention time. The initial cost was estimated by using the regression model which was described in the first quarterly report. The O&M cost covers the costs for all O&M activities, including processing feedstock, labor, and chemical use. The O&M cost was assumed to be 3% of the initial cost, which is based on Rofoff and Clarker (2010). A methane yield of 188 ml/g VS for the HS-AD was used to estimate total methane production of the HS-AD, which was based on the experimental results from the first quarterly report. The electricity and heat productions were estimated by using the equations below (Wang et al., 2016):

$$H_{HS-AD} = Y_{CH4}\ \xi\ \eta_{Heat} \qquad \text{(Eq.6)}$$

$$E_{HS-AD} = Y_{CH4}\ \xi\ \eta_{Electricity} \qquad \text{(Eq.7)}$$

where $H_{HS\text{-}AD}$ is the heat production from the CHP (kWh/d), $E_{HS\text{-}AD}$ is the electricity production from the CHP (kWh/d), Y_{CH4} is the methane yield (m^3/gVS), ξ is the low heating value of methane for HS-AD (kWh/m^3), η_{Heat} is the heat energy conversion efficiency of CHP, and $\eta_{Electricity}$ is the electricity energy conversion efficiency of CHP. For digestate, it was assumed that the digestate quality is the same as the compost quality.

For other different waste management options, including landfill, composting, and WtE, the LCCAs were estimated based on literature data. It was assumed that the landfill in this analysis is a 57-acre Class I landfill. The initial and O&M costs were estimated based on Table 5. The tipping fee in Hillsborough County can be classified as: a processable solid waste and non-processable solid waste (Table 7). Processable solid wastes are solid wastes that are capable of being processed through a Resource Recovery facility, while non-processable solid wastes are solid wastes that are not capable of being processed through a Resource Recovery Facility. For the landfill option, the tipping fee was considered as a part of the O&M costs in this analysis.

Table 5. Capital and O&M costs for landfill.

Item		Unit	Value	Reference
Capital cost	Clear and Grub	\$/acre	3,000	Duffy, 2015; US EPA, 2014
	Site Survey	\$/acre	8,000	
	Excavation	\$/acre	330,000	
	Perimeter Berm	\$/acre	16,000	
	Clay Liner	\$/acre	162,000	
	Geomembrane	\$/acre	35,000	
	Geocomposite	\$/acre	44,000	
	Granular Soil	\$/acre	64,000	
	Leachate System	\$/acre	12,000	
	QA/QC	\$/acre	100,000	
O&M cost	Operations (equipment, staff, facilities and general maintenance)	\$/tonne	2.76	Duffy, 2015; US EPA, 2014
	Leachate Collection and Treatment (assumes sewer connection and discharge cost of \$0.02/gal.)	\$/tonne	0.06	
	Environmental Sampling and Monitoring (groundwater, surface water, air gas , leachate)	\$/tonne	0.17	
	Engineering Services (consulting firms and in-house staff)	\$/tonne	0.33	

The composting system was assumed to be a windrow composting system due to its feasibility (Beattie, 2014). Assumptions made for composting are: 1) Initial cost includes paving, grading, fencing, building, leachate system, engineering cost, tub grinder, windrow turner, legal cost, screens, and front end loader (van Haaren, 2009); and 2) the compost is produced from 65.5% of the wet mass waste (Komilis & Ham, 2000). The initial cost for the composting was calculated based on Table 6, while the O&M cost for the composting were estimated a regression based model (Figure 7), which was based on the O&M costs for existing windrow composting systems (City of Palo Alto Public Works Department, 2008).

Table 6. Capital cost for composting system.

Item	Value ($/tonne)	Reference
Paving	27.5	van Haaren, 2009
Grading	2.1	
Fence	0.6	
Building	13.8	
Leachate system	2.8	
Engineering cost	13.8	
Tub grinder	6.9	
Windrow turner	5.5	
Legal cost	4.1	
Screens	5.5	
Front end loader	5.0	
Total cost	87.3	

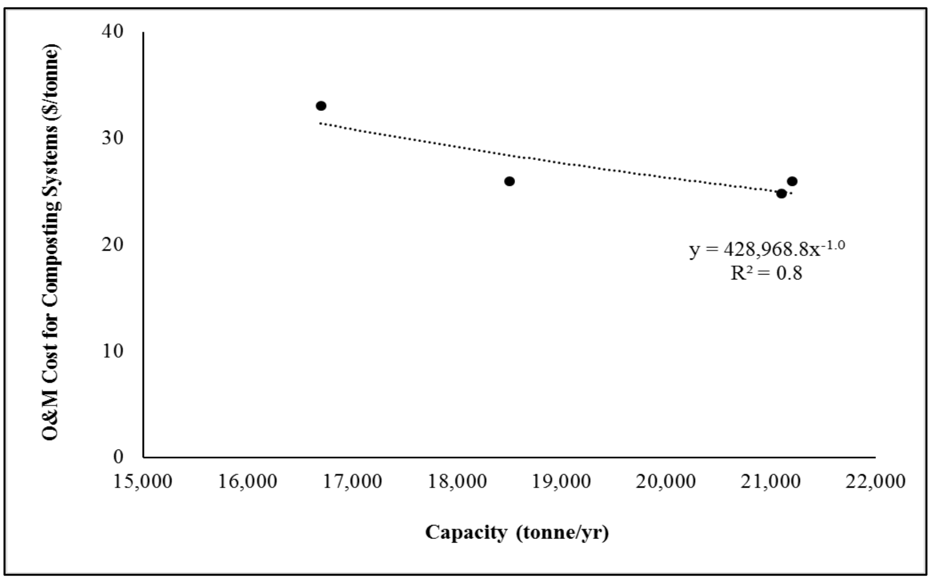

Figure 7. The O&M cost factor ($/tonne) as a function of the composting capacity (tonne/yr).

The WtE technology typically burns municipal solid waste (MSW) in an environmentally safe combustion system to generate electricity. Direct combustion is the most common technology for the WtE system (Funk et al., 2013). In this system, the MSW is directly burned to generate heat. This heat energy is converted to electrical energy. The initial cost for the WtE was estimated by using a regression model provided in UC Davis California Renewable Energy Center (2016). The O&M cost for the WtE plant in FL was $28/tonne, which was obtained from Funk et al. (2013) and SWANA (2012). It was assumed that the WtE facility was able to recover 0.026 tonne ferrous metal/tonne waste. This assumption was based on the ferrous metal recovery data from the McKay Bay Refuse-to-Energy Facility (Tampa, FL) (SWANA, 2009). The electricity produced (E_{WtE}, kWh) from the WtE was calculated according to Eq. (8) (Fernández-González et al., 2017):

$$E_{WtE} = 0.28\ (\frac{kWh}{MJ}) \times W \times R_f \times LHV_{WtE} \times n \qquad \text{(Eq.8)}$$

where W is the waste treated at the facility, R_f is the percentage of reject after mechanical treatment (%), LHV_{WtE} is the lower heating value of waste for WtE (MJ/t), and n is the yield of the WtE plants. The input parameters for the LCCA is shown in Table 7.

Table 7. All input parameters used in the LCCA.

Item	Valu e	Reference
Life cycle cost analysis period (yr)	25	This study
Discount or interest rate (%)	1.89	USIR, 2017
Escalation rate (%)	0.65	EERC, 2017
Average distance of travel (miles/hual)	50	This study
A haul loading (tonne)	30	Faucette et al., 2002
Transportation cost factor ($/miles)	0.1	
Methane yield for HS-AD (ml/gVS)	118	The first quarterly report
Solid reduction (%)	11	
Low heating value of methane for HS-AD (KWh/m^3)	9.94	Passos & Ferrer, 2015
Combined Heat and Power Efficiency: Heat (%)	49.5	BIOFerm, n.d.
Combined Heat and Power Efficiency: Electricity (%)	37.7	
Digestate or compost price ($/tonne)	11.2	Schwarzenegger, 2010
Electricity price ($/kWh)	0.08	EIA, 2017
Heat rate ($/kWh)	0.01	Moriarty, 2013
Tipping fee, non-processable solid waste ($/tonne)	31	Hillsborough County, 2016
Tipping fee, processable solid waste ($/tonne)	58	
Oyster shell cost ($/tonne)	0	This study
Landfill size (acre)	57	
Expected life time of landfill (yr)	50	
Compost production ratio (g compost/g wet mass waste)	0.656	Komilis & Ham, 2000
O&M cost factor for WtE ($/tonne)	28	Funk et al., 2013; SWANA, 2012
Percentage of reject after mechanical treatment for WtE (%)	89.4	Fernández-González et al., 2017
Lower heating value of waste for WtE (MJ/tonne)	8,000	Habib et al., 2013
Yield of the WtE	0.29	Fernández-González et al., 2017
Metal recovery (tonne ferrous metal/tonne waste)	0.026	SWANA, 2009
Metal price ($/tonne)	350	Funk et al., 2013

Result of Economic Analysis: LCCA results for four different options over 25 years are shown in Table 8. Among the options, WtE has the highest initial cost, followed by landfill, HS-AD, and composting. In particular, the windrow composting technology has the lowest costs (Wei & Wang, 2001). The landfill option has a high O&M cost, due to the high tipping fee. Other options could avoid the tipping cost, which is about $47,310,700 over 25 years. The C&T costs were not significant in the LCC results (< 1%). WtE, HS-AD, and composting options could gain large revenues from beneficial product sales (e.g. energy, compost). WtE could generate the largest revenue from electricity sales among other options, but the high initial and O&M costs lead the systems to be economically infeasible. For the HS-AD and composting systems, the annual revenues greatly exceeded the sum of the initial, O&M, and C&T costs, making the systems economically feasible. The most economical option in this analysis was the composting system, due to low initial and O&M costs.

It was found that the composting option was the most economically feasible through this analysis, but the results can change if the land acquisition is considered in the initial cost (Wei & Wang, 2001). In this analysis, the land acquisition was not included in the initial cost, which is a large portion of the initial cost for landfill and composting systems. Therefore, the land acquisition will be considered in the next LCCA.

Table 8. LCC results for different options.

Items	Unit ($)			
	Landfill	Waste to Energy	HS-AD	Composting
Initial cost	25,542,000	101,602,100	20,072,300	4,808,200
O&M cost	50,912,400	30,495,900	11,909,700	10,670,000
C&T cost	181,600	181,600	181,600	181,600
Tipping cost saving	0	47,310,700	47,310,700	47,310,700
Electricity sale	0	54,823,900	15,472,000	0
Heat sale	0	0	2,082,700	0
Compost (or digestate) sale	0	0	2,349,400	8,002,100
Recovered metal sale	0	9,992,800	0	0
LCC	76,636,000	20,152,200	-35,051,200	-39,653,000
LCC per wet waste handled for 25 years ($/tonne)	56	15	-25	-29

DISSEMINATION ACTIVITIES

1. Oral presentation at WEF Residuals and Biosolids conference in Seattle, WA. April 11th, 2017.

2. Poster presentation at Florida Water Resources Conference 2017 (FWRC) in West Palm Beach, FL. April 24th, 2017.

3. Poster Presentation at the USF Undergraduate Research and Arts Colloquium. April 6, 2017.

METRICS

1. List graduate student or postdoctoral researchers funded by THIS Hinkley Center project:

Last name, first name	Rank	Department	Professor	Institution
Dixon, Phillip	PhD Student	Civil/ Environmental Engineering	Ergas	USF
Lee, Eunyoung	PhD Student	Civil/ Environmental Engineering	Zhang	USF
Wang, Meng	Postdoctoral Researcher	Civil/ Environmental Engineering	Ergas	USF

2. List undergraduate researchers working on this Hinkley Center project:

Last name, first name	Rank	Department	Professor	Institution
Bittencourt, Paula	BS student	Mechanical Engineering	Ergas	USF
Jimenez, Eduardo	BS Student	Civil & Environmental Engineering	Ergas/Zhang	USF
Casimir, Lensey	BS Student	Civil & Environmental Engineering	Ergas	USF
Stolte Bezerra Lisboa Oliveira, Deborah	BS Student	Chemical & Biomedical Engineering	Zhang	USF
Stolte Bezerra Lisboa Oliveira, Luiza	BS Student	Chemical & Biomedical Engineering	Zhang	USF

3. List research publications resulting from this Hinkley Center project.

   No peer reviewed publications have resulted from this project thus far.

4. List research presentations resulting from this Hinkley Center project.

	Title	Conference
1	P. Dixon, P. Bittencourt, E. Lee, M. Wang, E. Jimenez, Q. Zhang, S.J. Ergas. Effects of Biosolids Addition and Alkalinity Sources on High-Solids Anaerobic co-Digestion (HS-AcD) of Food Waste and Green Waste	WEF Residuals and Biosolids Conference, Seattle WA April 11, 2017
2	Phillip Dixon, Paula Bittencourt, Eduardo Jimenez, Dr. Meng Wang, Eunyoung Lee, Dr. Qiong Zhang, and Dr. Sarina Ergas. Alkalinity and Temperature Effects on Methane (CH_4) Yield in High-Solids Anaerobic co-Digestion (HS-AcD)	Florida Water Resources Conference (FWRC), West Palm Beach FL, April 24th, 2017
3	P. Bittencourt, E. Jimenez, P. Dixon, M. Wang, and S. J. Ergas. Effects of Alkalinity and Temperature on High-Solids Anaerobic co-Digestion	University of South Florida Undergraduate Research Colloquium, April 6, 2017

- NOTE: Paula Bittencourt and Eduardo Jimenez won the award for OUR Excellence in Research Awards at the 2017 USF Undergraduate Research and Arts Colloquium.

5. List who has referenced or cited your publications from this project?

The following publications, which resulted from the Phase I project has been cited one time: Hinds, G.R., Mussoline, W., Casimir, L., Dick, G., Yeh, D.H., Ergas, S.J. (2016) Enhanced methane production from yard waste in high-solids anaerobic digestion through inoculation with pulp and paper mill anaerobic sludge, Environmental Engineering Science, 33(11): 907-917.

6. How have the research results from this Hinkley Center project been leveraged to secure additional research funding?

   - Phillip Dixon was partially supported by an NSF funded Partnership in International Research and Education (PIRE) grant during the 2017 academic year.
   - Paula Bittencourt and Eduardo Jimenez were partially supported (40%) by funds from the USF College of Engineering Research Experience for Undergraduates (REU) program.
   - A proposal was submitted to the Environmental Research and Education Foundation (EREF) entitled, "Enhanced Bioenergy Production from Lignocellulosic Wastes."

- A proposal was submitted to USDA entitled, "Production of high value added products from sugarcane bagasse via high solids anaerobic digestion and thermo-catalytic conversion."

7. What new collaborations were initiated based on **THIS** Hinkley Center project?

   Collaborations were initiated with Drs. John Kuhn and Babu Joseph on the production of value added products from biogas produced via HS-AD.

8. How have the results from THIS Hinkley Center funded project been used (not will be used) by FDEP or other stakeholders? (1 paragraph maximum).

At this time, the research has not been used by FDEP. The research has been disseminated to Hillsborough County for possible future biosolids and MSW management alternatives.

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